

A MECHANICAL RECTIFIER  
FOR  
AIRCRAFT  
BY  
GEORGE LITTLE BLISS, JR.

Thesis  
B56

Library  
U. S. Naval Postgraduate School  
Annapolis, Md.











A MECHANICAL RECTIFIER

for


AIRCRAFT

by

George Little Bliss Jr.  
Lieutenant Commander, United States Navy

Submitted in partial fulfillment  
of the requirements  
for the degree of  
MASTER OF SCIENCE

United States Naval Postgraduate School  
Annapolis, Maryland  
1950



Thesis  
B56

This work is accepted as fulfilling  
the thesis requirements for the degree of

MASTER OF SCIENCE  
in  
ELECTRICAL ENGINEERING

from the  
United States Naval Postgraduate School



## PREFACE

This investigation was made<sup>at</sup> the US Naval Postgraduate School, Annapolis, Maryland, during the Academic Year 1949-50. Its successful completion is to a large extent the result of the help and information of Mr. Otto Jensen and Mr. John Kuzmack at the ITE Circuit Breaker Co. The information on the Orthonol Cores was obtained through the excellent cooperation and help of the Magnetic Amplifier Subsection of the US Naval Ordnance Laboratory; who, by permitting the author to use their equipment, shop spaces, and an Orthonol core, made it possible to obtain the characteristics upon which the calculations were based. Mr. McKee of this section was particularly helpful during this portion of the investigation.

Professor Allen E. Vivell, in his capacity as faculty adviser, gave unsparingly of his time and helped solve many thorny problems which arose from time to time during the investigation.

The author is also greatly indebted to ITE for the use of applicable circuit diagrams and wave forms from their two papers on the mechanical rectifier. And, to the Eclipse-Pioneer Division of Bendix Aviation Corporation for technical data on their 90 KVA alternator.





# TABLE OF CONTENTS

## Chapter I Introduction

1. General	1
2. The Basic Theory of Operation	2
3. The Step	6
4. The Step Length and Safety Step	8
5. The Need for Pre-excitation	10
6. Voltage Control	12
7. The Selection of Core Material	16

## Chapter II General Design Considerations

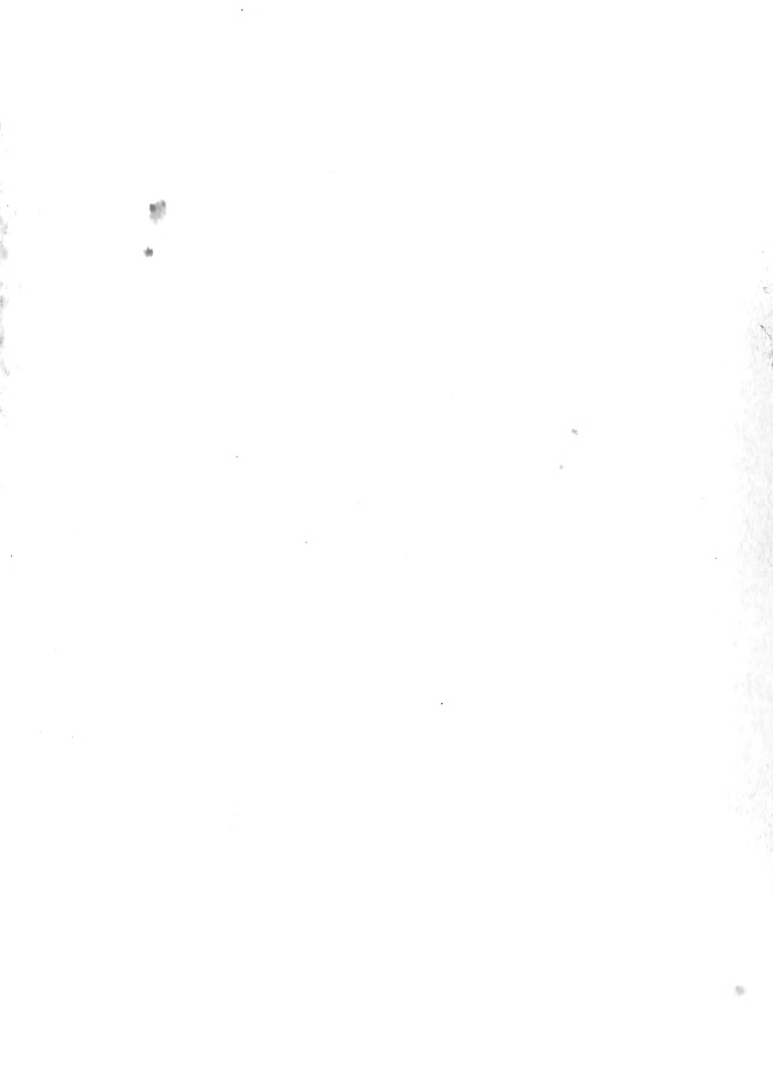
1. The Limitations Imposed by Voltage and AC Source Inductance	18
2. Voltage Control	23
3. The Effect of Load Characteristics	24

## Chapter III Selection of a Core

1. Experimental Data	26
2. The Determination of Probable Step Length	34
3. The Determination of Optimum Core Area	40
4. Final Calculation of Step Location and Length	47
5. The Effect of Frequency and Voltage Fluctuations	50
6. Manufacturing and Handling Problems	53

## Chapter IV Pre-excitation

1. General	57
2. AC Pre-excitation	58
3. DC Pre-excitation	64
4. Base Load	67



Chapter V	The Contact Mechanism	
1.	Requirements and Limitations	70
2.	Installation and Adjustment	71
3.	The RC Parallel Circuit	74
Chapter VI	Circuit Protection	83
Chapter VII	Performance	
1.	Weight Estimate	85
2.	Volume Estimate	86
3.	Losses and Efficiencies	86
4.	Power Factor	89
Chapter VIII	Operation	
1.	Contact Timing	90
2.	Starting and Stopping	90
Chapter IX	Conclusions	93
Appendix I	Determination of the Core Characteristics	97
Appendix II	Excerpts from Floris Koppelman's paper on the Mechanical Rectifier	109



# LIST OF ILLUSTRATIONS

Fig. No.	Title
1.	Elementary Circuit
2.	Commutation of Contact Converter
3.	Current and Voltage Conditions when Energizing a Reactor at Zero Voltage Point
4.	Energizing a Saturable Reactor from an AC source (Resistive Circuit)
5.	Load Current Variations
6.	Energizing a Saturable Reactor from an AC Source (Inductive Circuit with AC Pre-excitation)
7.	Commutation of Contact Converter with Saturable Reactors
8.	Voltage Control
9.	Magnetic Voltage Control - No Delay
10.	Magnetic Voltage Control - Magnetic Delay
11.	Star Pointed and Bridge Connection
12.	Commutating Voltage Area
13.	Overlap Control
14.	Hysteresis Loop size as a Function of Step Length
15.	Hysteresis Loop - .6 Milliseconds
16.	Effect of Frequency on Hysteresis Loop - .6 Milliseconds
17.	Hysteresis Loop - .3 Milliseconds
18.	Effect of Frequency on Hysteresis Loop - .3 Milliseconds
19.	DC Hysteresis Loop



Fig. No.	Title
20.	Step Position
21.	Core Dimensions nomenclature
22.	Hysteresis Loop nomenclature
23.	Core Weight and Output Voltage vs Core Height at 400 cycles 120/208 volts input
24.	Step Location vs. Load current
25.	Output Voltage vs. Load current
26.	Effect of improper matching of component cores on the shape of the overall hysteresis loop.
27.	Effect of plastic deformation on the shape of the hysteresis loop
28.	Supporting the cores
29.	Y connected AC Pre-excitation
30.	Delta Connected AC Pre-excitation
31.	AC Pre-excitation wave forms for breaking step
32.	AC Pre-excitation wave forms for making step
33.	Effect of Step on the AC Pre-excitation current wave form
34.	Saturation curve for laminated silicon steel
35.	Radial Installation of Contacts
36.	Push rod and contact movements
37.	Arcing characteristics of possible contact material
38.	German Leaf Spring Contact
39.	Core Windings
40.	Composite Wave forms of a Mechanical Rectifier
41.	Complete circuit diagram





Fig. No.	Title
42.	Overall Efficiency vs. Load current
A43.	ITE Test Circuit for measuring magnetization and commutation curves of core material
A44.	Vectormeter test loop
A45.	Vectormeter
A46.	Hysteresis loop for 1.2 millisecond step
A47.	Hysteresis loop for .2 milliseconds step
A48.	Circuit for comparing 60 cycle and 400 cycle hysteresis loops.



## SYMBOLS AND ABBREVIATIONS

ITE	ITE Circuit Breaker Co., Philadelphia, Penna.
NOL	Magnetic Amplifier Subsection, US Naval Ordnance Laboratory
i	Instantaneous current
K	Contacts
$i_s$	Short Circuit current during commutation
$\Delta T$	Step Length in milliseconds
$A_{Fe}$	Iron core area
E	RMS Voltage
N	Number of turns of the main winding
$\Delta B$	Change in flux (Intrinsic) in the core during the step in webers
$\Delta$	Delay in commutating time
$e_c$	Instantaneous commutating voltage
$L_s$	Total effective inductance in the commutating circuit
$d_m$	Mean Diameter of the core
W	Width of the core
a	Area of the hysteresis loop
z	Per unit change in pre-excitation current
$I_p$	AC Pre-excitation current
$N_p$	Number of turns of AC pre-excitation on main core
AT	Ampere turns



## SUMMARY

This is an attempt to design conservatively a mechanical rectifier with a rating of 9.6 KW at 115 volts DC for large aircraft, using for its AC supply, the Eclipse 400 cycle, 90 KVA alternator.

This design gave a weight of 3.2 pounds per kilowatt and an efficiency ranging from 82.7% at 1/4 load to 92.1% at rated load. The entire unit could be put into a space 9 inches x 9 inches x 15 inches.

This type of rectifier has as its primary advantages, simple voltage control, low weight, high conversion efficiency, no altitude limitation, and no reasonable temperature limitations. (100°C ambient air)

Its chief disadvantages are, its requirement of a large capacity power source to give a reasonable power output without resort to transformers; a power factor of .85 lagging, at rated load; and a mechanical sensitivity of the contact mechanism. The extent of this mechanical sensitivity will not be known until a unit has been built and tested.

This unit was designed to have the mechanical portion driven by the same gear train which drives the AC power source. This would appear to be almost obligatory for aircraft applications, to give greater reliability and to reduce weight.

The mechanical rectifier is a good solution for the rectification problem for large aircraft and an excellent solution for large aircraft flying at high speeds at high



altitudes or where high ambient air temperatures have become a problem.





## CHAPTER I

### INTRODUCTION

#### 1. General

This was a preliminary investigation to determine the advisability of utilizing the mechanical rectifier for the conversion of 400 cycle AC to DC in aircraft. As an aid to the investigation, it was decided to design a rectifier having a nominal rating of 9.6KW at 115 volts DC with provision for voltage regulation and able to deliver a peak overload of 500% rated current. No previous work had been done at 400 cycle to the knowledge of the author. In fact, only a limited amount of work has been done in the conventional power frequencies. This had been primarily on large fixed installations. The original work was done by Siemens-Schuckert, Berlin, Germany, before and during War II. It has been carried on since the War, by the ITE Circuit Breaker Co. of Philadelphia. Jensen (1), Rolf (3).

This investigation was only a preliminary one, since no information was available in the 400 cycle range and any complete analysis would have involved actually building and testing a complete installation. This was obviously impossible within the limitation of time and funds available for the project. The results obtained, therefore, are based on the tests of one Orthonol Core supplied by the Magnetic Amplifier Subsection of the US Naval Ordnance Laboratory, hereafter referred to as NOL; and the basic



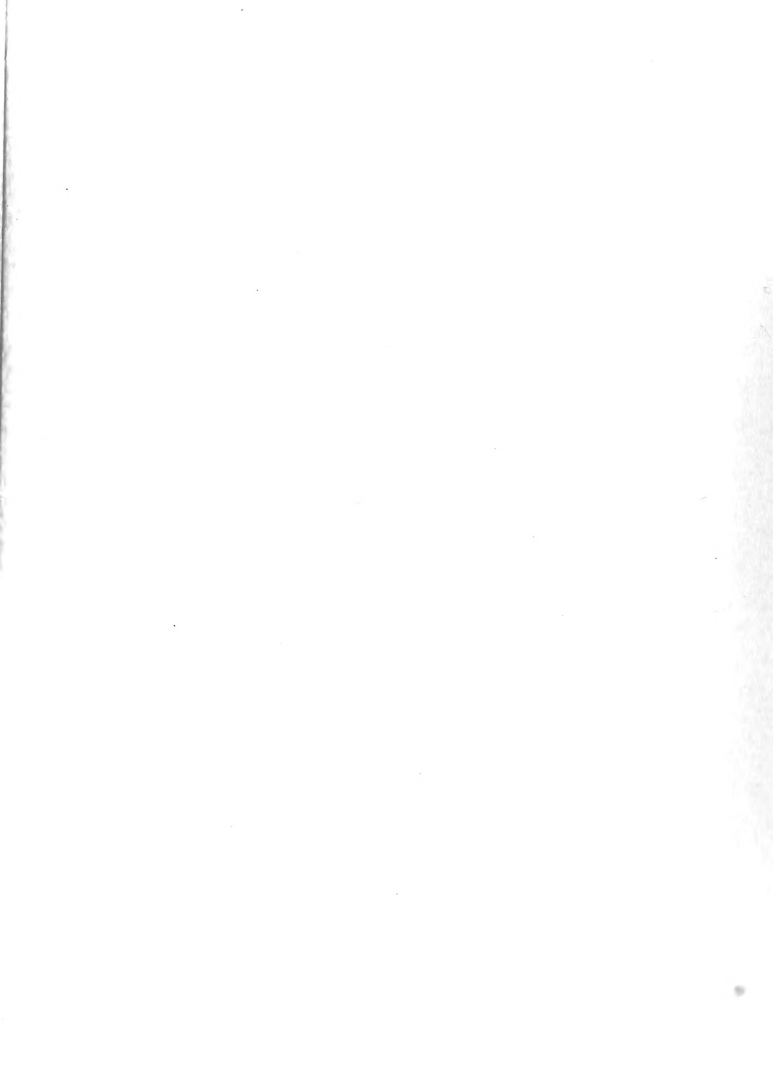
relations developed by Floris Koppelman (2) and Dr. Erich Rolf, both of Siemens. Dr. Rolf has since prepared a rather complete study of mechanical rectifier design at conventional power frequencies for ITE. Rolf (3).

This investigation was undertaken because information based on work in the conventional power frequencies indicated that it was possible to achieve high conversion efficiency and good voltage control with a relatively simple mechanism, which combined these advantages with low weight and space requirements.

## 2. The Basic Theory of Operation.

The basic theory of operation of the Mechanical Rectifier is not very well known since the original concept was not developed until 1935 and was not known in this country until 1946. The mechanical rectifier operates by connecting the AC bus to the correct polarity DC bus during the time interval during which the AC bus can deliver energy. This connection of course must be terminated before the voltage of the AC bus falls sufficiently so that the current will reverse. Also, in any multi-phase system, there must be some provision for shifting the load from phase to phase or commutating as the process is now familiarly called.

In a conventional rectifier, such as a selenium oxide, this is taken care of by the nature of the conducting medium. In the mechanical rectifier, however, the current can flow in either direction with equal ease and some provision must be made to time properly the making and breaking of the



Considering now an elementary circuit to explain the basic theory upon which the unit depends for its operation; refer to Fig. 1, and make the following assumptions:

A. General Conditions

1.  $L_1$  and  $L_2$  are very much less than  $L_L$
2.  $K_2$  closes automatically when  $E_2$  equals  $E_1$ .

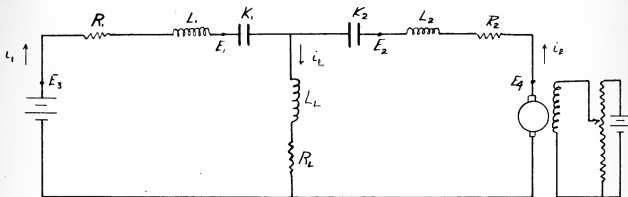
B. For the initial conditions

1.  $E_2$  is less than  $E_1$
2. As a result,  $K_1$  is closed and  $K_2$  open.
3.  $i_1$  has reached a steady state condition

C. Dynamic conditions

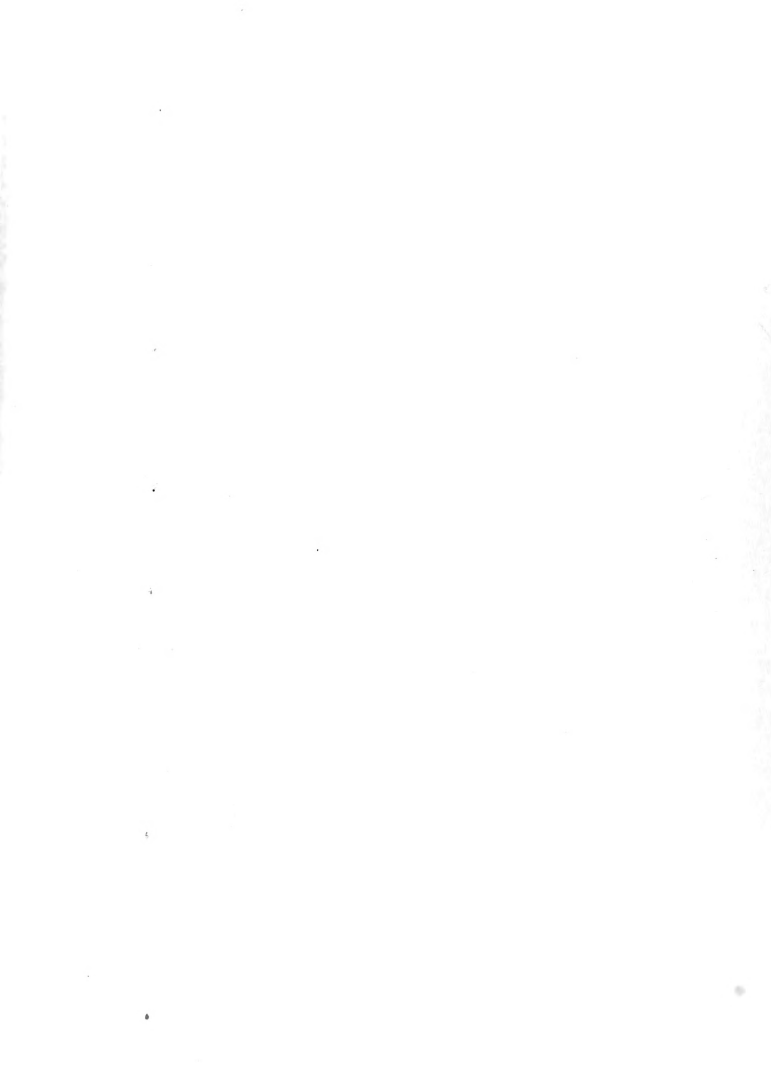
1.  $i_L$  will remain constant if  $E_4$  is increased very rapidly to a value such that  $E_4 - i_L Z_2$  equals  $E_1$

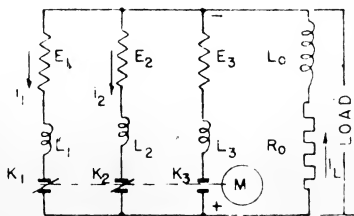
If all of these assumptions are considered,  $i_1$  will have decreased to zero and  $i_2$  will equal  $i_L$ . Thus, the commutation from supply 1 to supply 2 will have been completed.



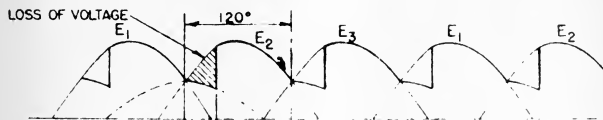
Elementary circuit

Fig. 1

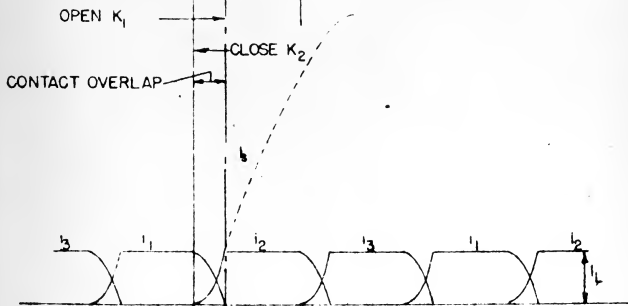




a- SCHEMATIC CONNECTIONS

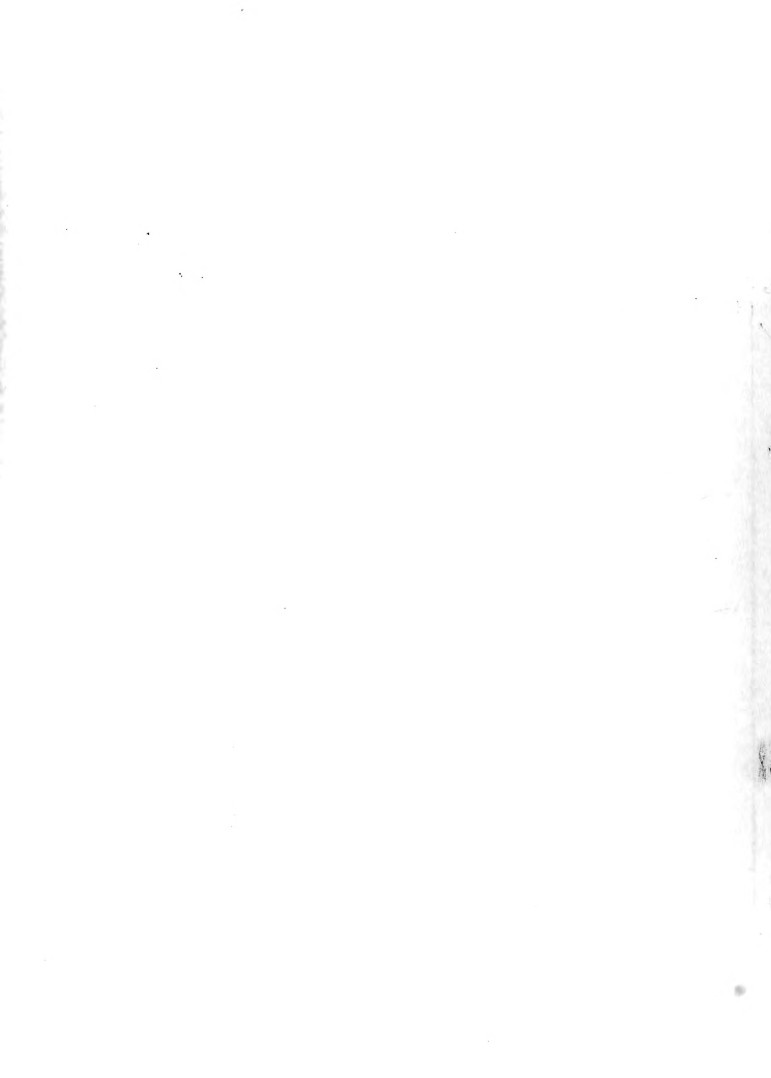


b- VOLTAGE DIAGRAM



c- CURRENT DIAGRAM

FIG 2  
COMMUTATION OF CONTACT CONVERTER





If we now substitute for the voltage sources used in Fig. 1, the alternator shown in Fig. 2, we can use conventional AC transient analysis. If we again assume that  $L_1$  and  $L_2$  are small as compared with  $L_L$ , the following analysis will apply. Considering the closing time of  $K_2$  in Fig. 2, the current  $i_2$  will rise in accordance with the normal RL circuit transient response as shown in Fig. 3. Since the portion in which we are interested is only a fraction of a cycle and the resistance is necessarily small, the time constant can be assumed to be infinite and  $i_2$  can be represented by a cosine wave displaced so that it starts from zero.

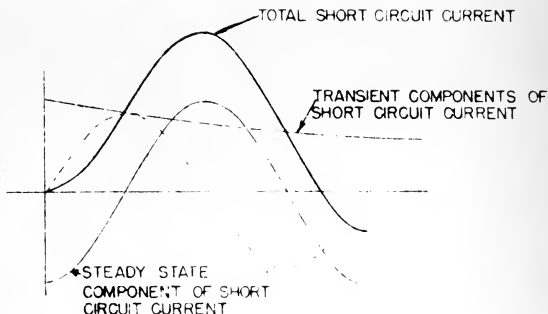
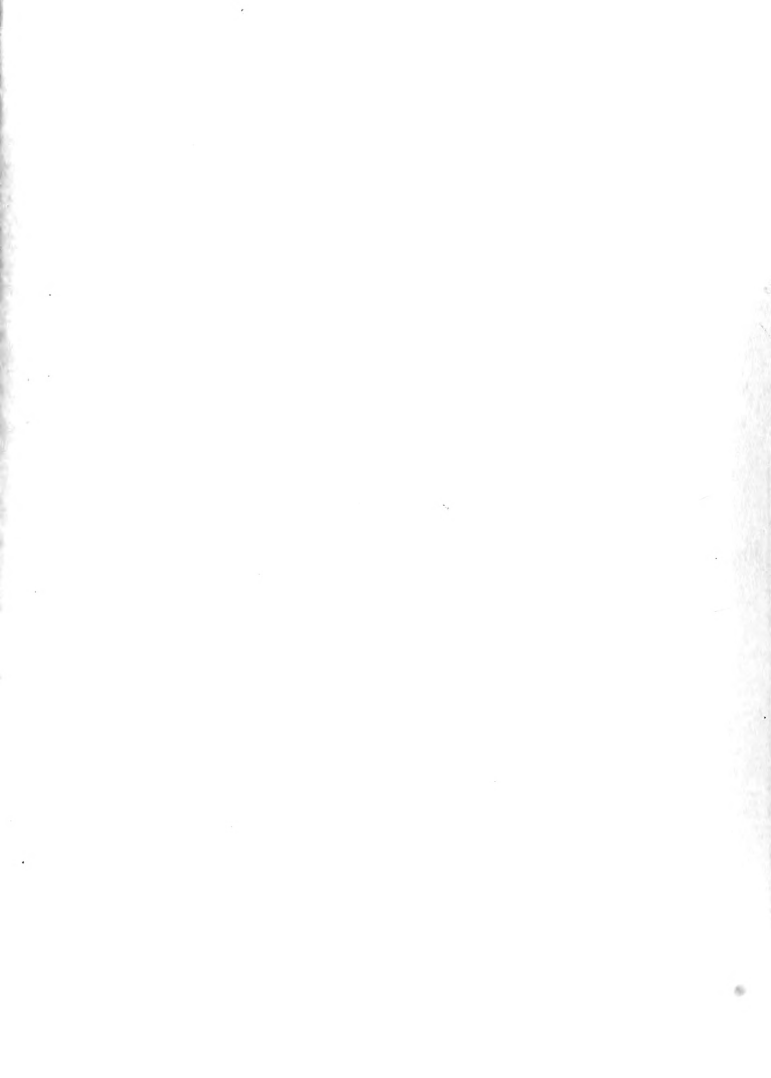


FIG 3

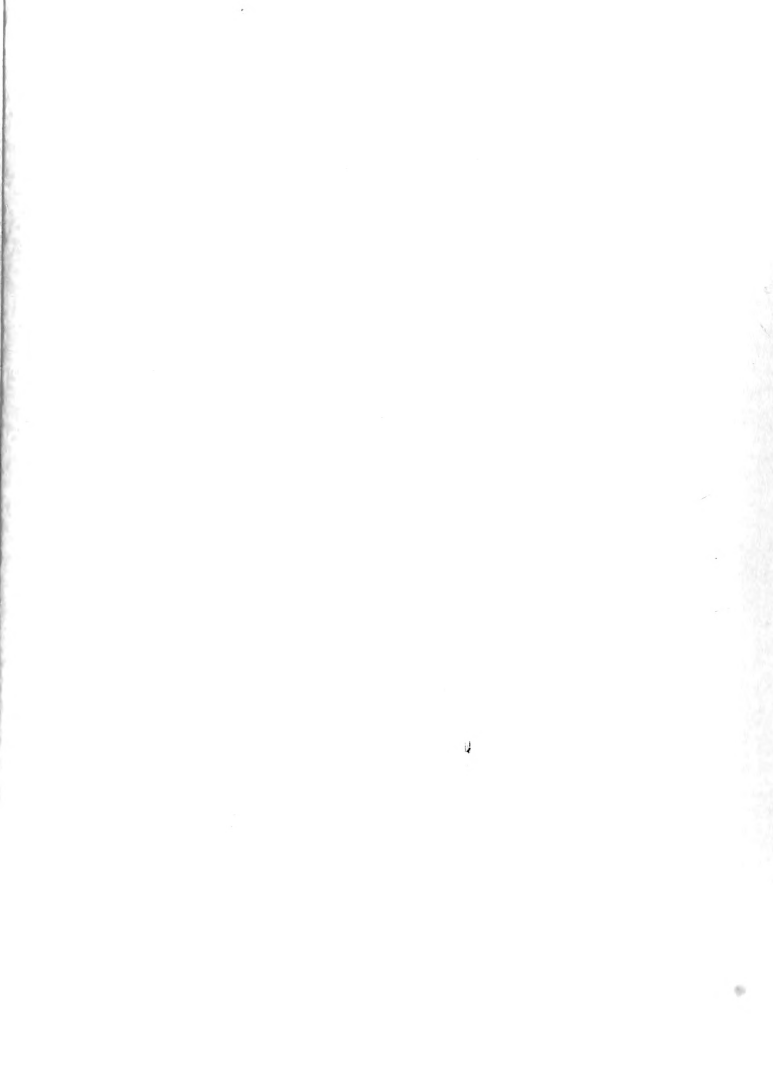
CURRENT & VOLTAGE CONDITIONS WHEN  
ENERGIZING A REACTOR AT ZERO VOLTAGE  
POINT.

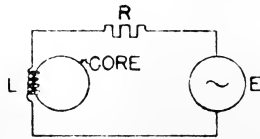


The current in the load circuit can be assumed to remain constant as a result of the large value of  $L_L$  and as a result the current  $i_1$  will decay in the form  $1 - i_{s_{max}} \cos \omega t$ .  $i_{s_{max}}$  is the maximum short circuit current which could flow. At the time that  $i_g$  equals  $i_L$ ,  $i_1$  will have decayed to zero and the commutation will be completed. At this point, of course, it is necessary for the switch  $K_1$  to open to prevent reversal of  $i_1$ , furthermore, it must open at exactly this moment to insure arc free operation. This point, however, is a function of load current, AC input voltage, and frequency; as a result, it will shift as these variables are changed. For a three phase, star pointed connection, the wave forms would look like Fig. 2. The shaded voltage area is the change in flux linkages required for commutation. This results in a reduction in DC output voltage. It will be referred to in this paper as reactive voltage drop.

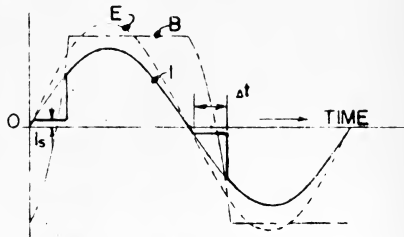
### 3. The Step

The physical impossibility of making the contacts always open at zero current is the problem which plagued all efforts to design a practical mechanical rectifier until Floris Koppelman reasoned that if the current could be made to remain at zero for a finite length of time, it would be possible to design a mechanical unit which would open and close the contacts during this period. The device which accomplishes this, and as a result is the heart of the unit is the saturable reactor. If a saturable reactor is placed in the circuit through which  $i_1$  is flowing; as current reverses, the entire voltage will appear across





a- SCHEMATIC DIAGRAM



b- CURRENT, FLUX & VOLTAGE  
CONDITIONS

FIG 4  
ENERGIZING A SATURABLE REACTOR  
FROM A A.C. SOURCE (RESISTIVE CIRCUIT)

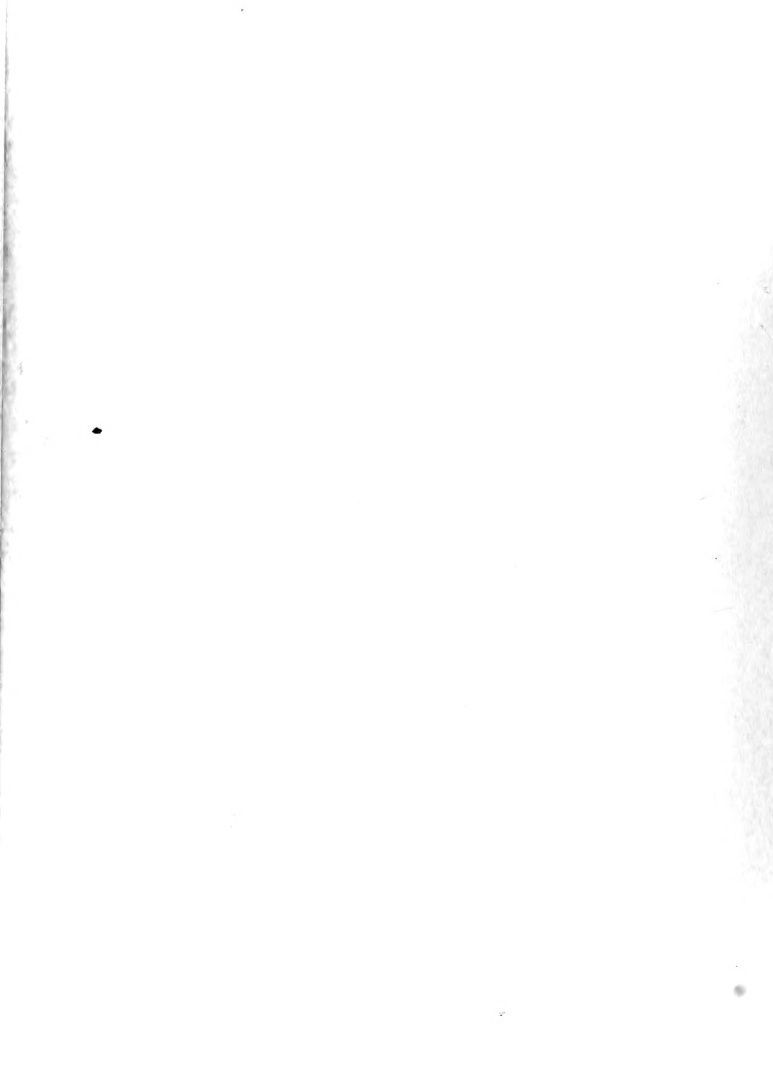


the turns on the saturable core during the remagnetization time. The resulting current step,  $\Delta T$ , will have a length which is a function of core material, the area of the core,  $A_{Fe}$ , the voltage across it,  $E$ , and the number of turns,  $N$ .

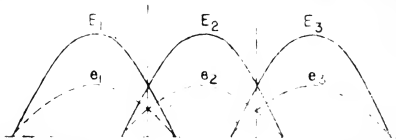
$T = \frac{\Delta B A_{Fe} N}{E}$  Jensen (1). It must be continually kept in mind that  $B$  is the intrinsic magnetization, not the total amount of flux in the core.  $B = \beta \mu H$ . There will still be a small amount of current flowing which is providing the ampere turns required to remagnetize the core. This is small however when compared with the load current. The effect of a saturable core in a simple circuit is shown in Fig. 4.

#### 4. The Step Length and the Safety Step.

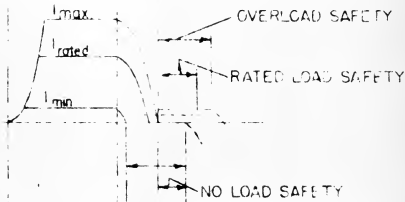
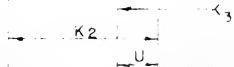
Referring again to the shift in the zero current point as a function, primarily, of load current and the inductance of the AC circuit, the current step must be made long enough so that it will include the time that the contact opens, regardless of what the electrical conditions may be. If this were not true, there would be an arc and the contacts would be destroyed. The two extremes are normally the minimum and maximum load as shown in Fig. 5. In most rectifiers, provision is made for shifting the timing of the contacts to compensate some for this, and as a result, reduce the size of the core required. This is done on the premise that the load current will not change any faster than the contact time can be shifted. This does not appear to be a reasonable assumption for aircraft applications and so the step was necessarily designed for fixed contact timing.



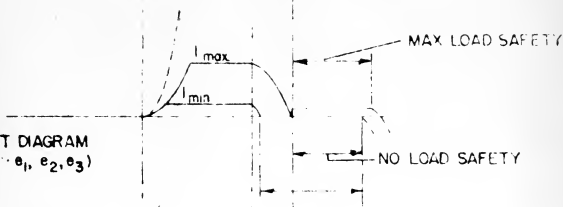




a VOLTAGE DIAGRAM



b CURRENT DIAGRAM  
(voltage  $E_1, E_2, E_3$ )

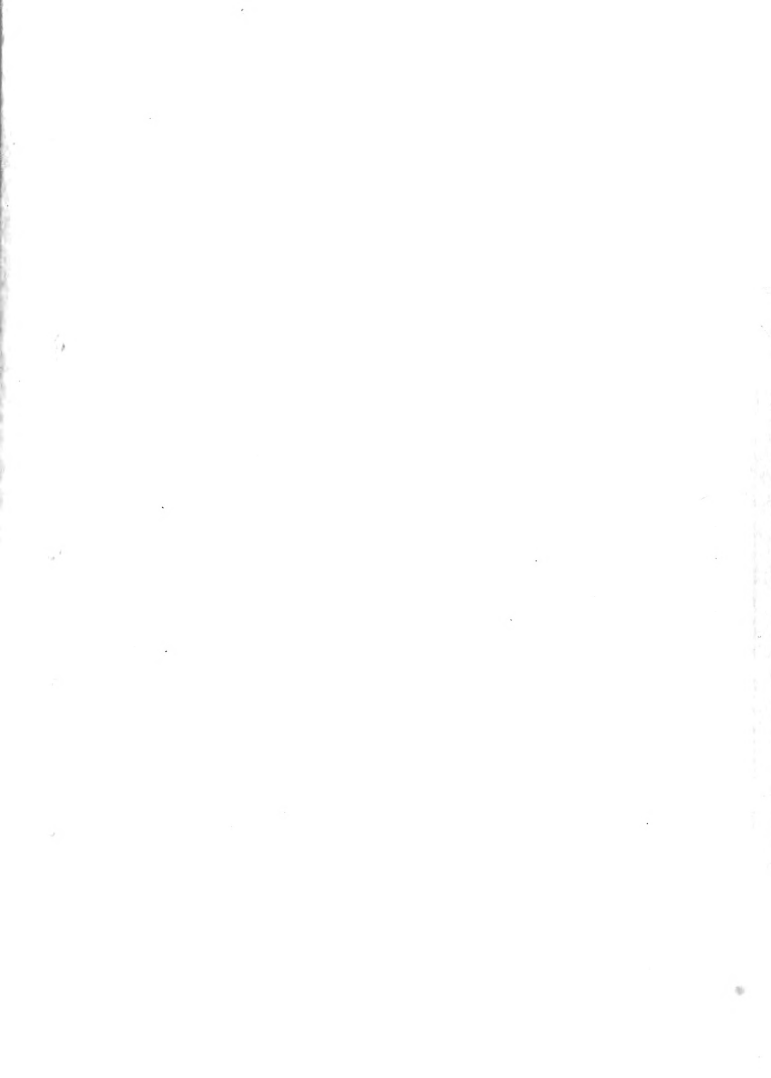


c CURRENT DIAGRAM  
(voltage  $e_1, e_2, e_3$ )



d CURRENT DIAGRAM  
(voltage  $E_1, E_2, E_3$  but  
increased commutating  
circuit reactance)

FIG. 5  
LOAD CURRENT VARIATION

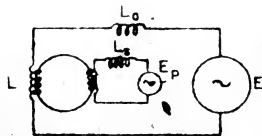


In addition to the actual step length required by the initial conditions, it is also necessary to have an additional time designated as the safety step. This is the portion of the step which extends after the contact opens as further insurance that the contacts will be far enough apart, when the voltage across the reactor collapses and appears across the contacts, that there will be no possibility of flash over. Koppelman (2) states that if the contacts open at a speed of 1 meter per second, a safety step of  $10^{-5}$  seconds is sufficient. This is always made longer though to take care of manufacturing and installation deficiencies.

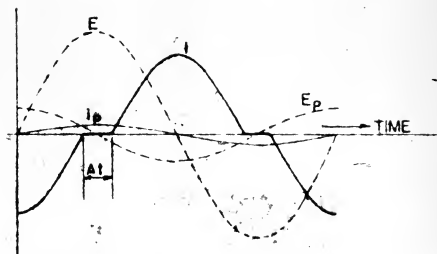
#### 5. The Need for Pre-excitation.

The small amount of magnetizing current flowing may still produce some arcing, this would not be a serious problem if the operation did not repeat so frequently. The magnetizing current can be controlled by providing a pre-excitation winding which will provide the necessary number of ampere turns for the remagnetization. This can be seen by referring to Fig. 6 which shows the results if AC pre-excitation of the proper phase and power is provided. In practice, sufficient pre-excitation is used so that the current in the main winding does not reverse but continues to flow with a small positive value during the step. This is done so that when the contacts open, a small positive voltage will exist across the contacts during the safety step, from the inductance in the circuit, before the high negative voltage which is across the core appears across





a SCHEMATIC DIAGRAM



b CURRENT VOLTAGE CONDITIONS

FIG-6

ENERGIZING A SATURABLE REACTOR FROM AN A.C. SOURCE  
(INDUCTIVE CIRCUIT AND WITH A.C. PRE-EXCITATION.)

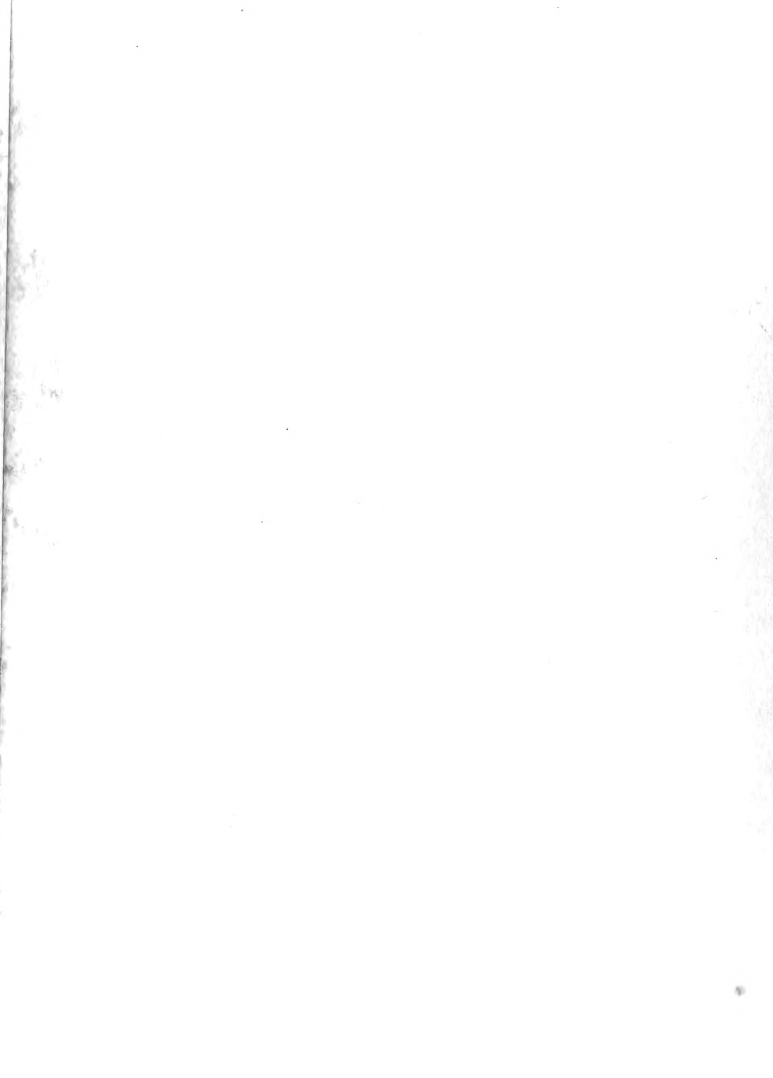


the contacts. This change in polarity is merely another safety precaution to insure that any arc which may start from metal particles in the space between the contacts will go out as the current goes through zero.

#### 6. Voltage Control

We now have a unit, Fig. 7, which will deliver a DC voltage that is a function of the AC input voltage and the inherent voltage regulation of the unit. If the time of contact closing were delayed an angle  $\alpha$  from the closing time of  $K_2$  in Fig. 2, to a later time, it would result in a lower DC output voltage. This can be best understood by referring to Fig. 8. This system is used in installations with provisions for shifting the contact time.

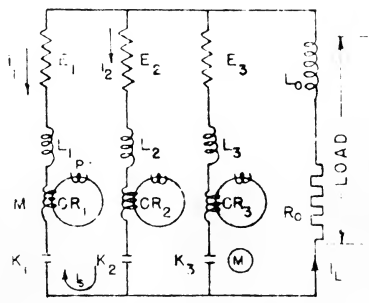
There is another system of voltage control called magnetic delay which requires no contact shift. This makes the contact mechanism much simpler to build and operate. The normal disadvantage is that it requires a large break reactor. This is not a disadvantage in this design since a large one is required for the severe overload requirements. Referring now to Fig. 9b, for maximum DC output voltage, the commutating reactor provides no delay in the build up of the phase current. However, as in Fig. 10, when some voltage control is desired, the amount that the core has been premagnetized, will determine the reduction in DC output voltage the same way as in Fig. 8, for the mechanical system. Area  $A_1$  is the reduction in DC voltage from magnetic delay and area  $A_2$  from the reactive voltage drop.



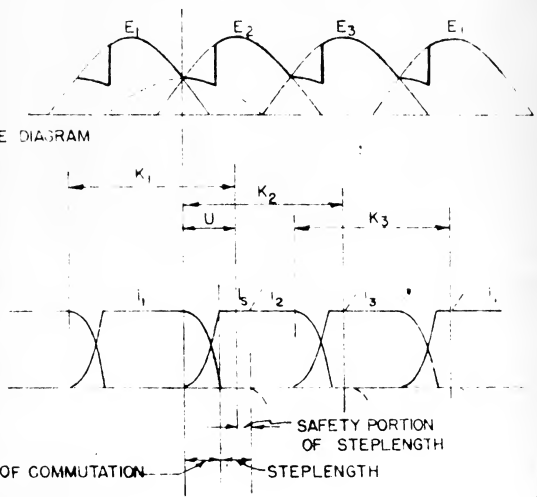




a SCHEMATIC  
DIAGRAM

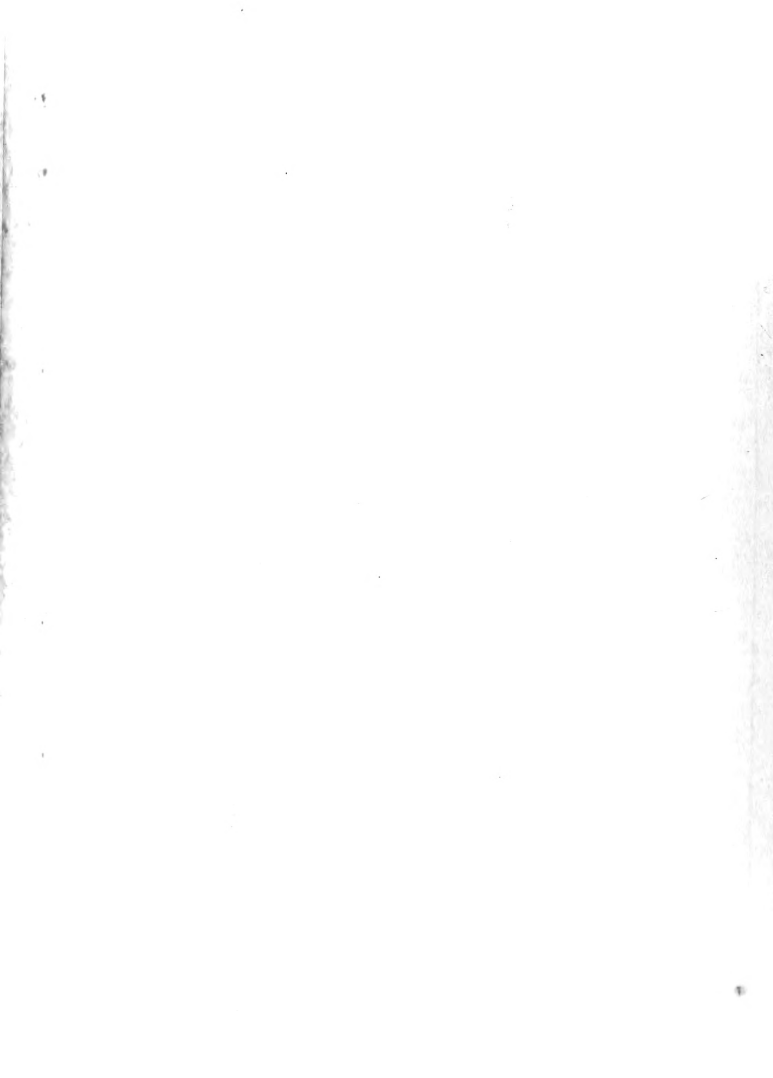


b VOLTAGE DIAGRAM



c CURRENT DIAGRAM

FIG 7  
COMMUTATION OF CONTACT CONVERTER  
WITH SATURABLE REACTORS (COMMUTATING  
REACTORS)



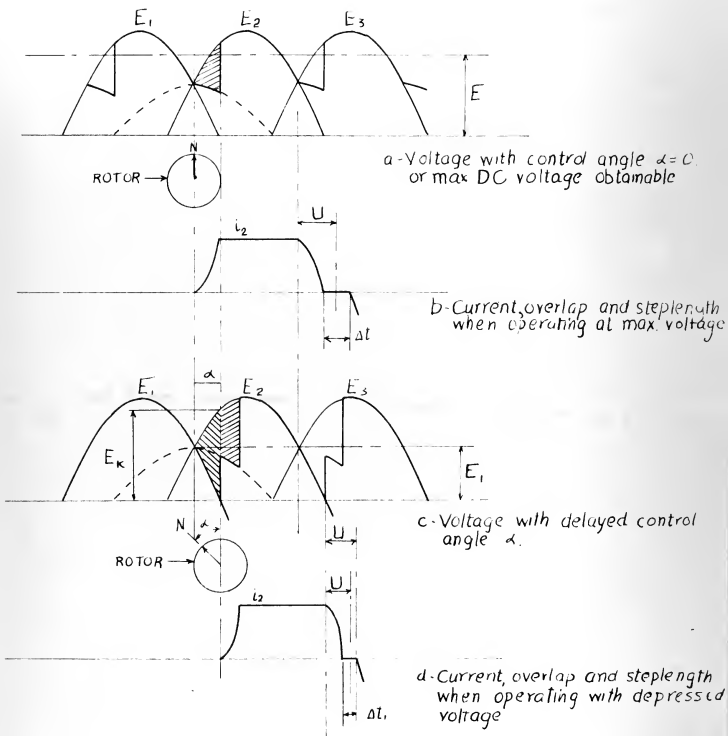
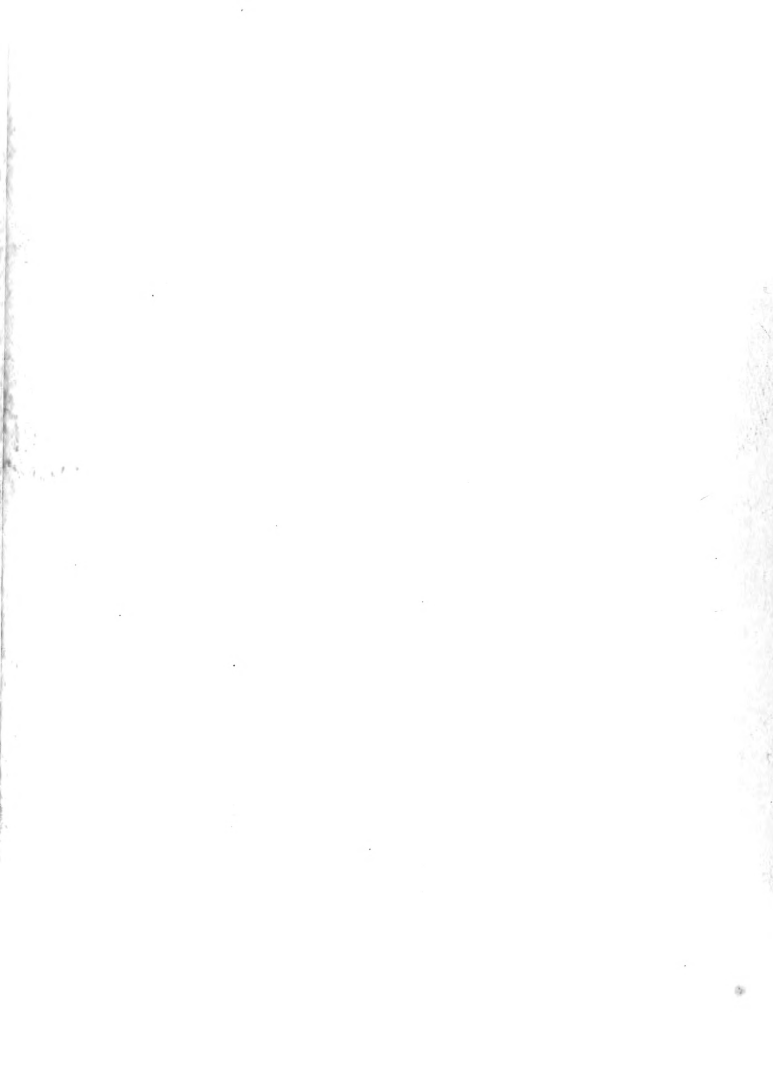
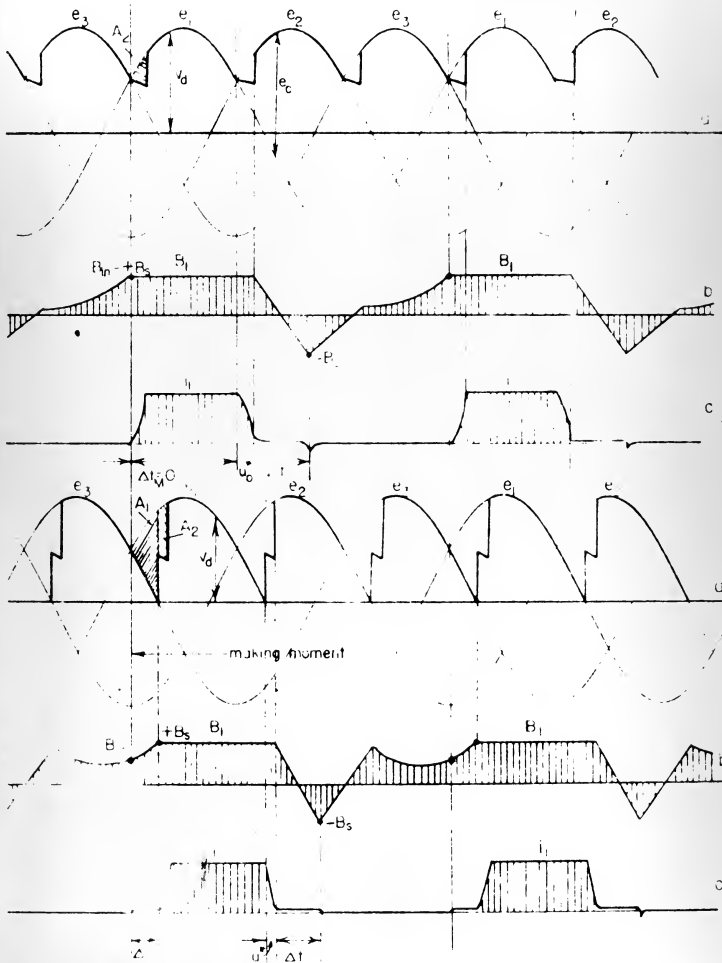


FIG-8

VOLTAGE CONTROL







## 7. The Selection of Core Material

The step length as was pointed out before can be calculated by the formula,  $T = \frac{\Delta B N A_{Fe}}{E}$ , where  $\Delta B$  depends upon the material in the core. Since the step length is directly proportional to  $\Delta B$  it would seem best to have the maximum  $\Delta B$  available during the step, and the minimum outside of the step. This immediately dictates the use of a new class of magnetic materials which have practically a rectangular hysteresis loop. The material which is now being used was originally developed in Germany by a subsidiary of Siemens as Permenorm 5000Z. This is essentially a 50% iron, 50% nickel alloy. The procedure for getting the optimum magnetic characteristics was brought over by Mr. Jensen and is discussed in some detail in Ref. (1). The Orthonol core used is an improvement of 5000Z developed by NOL and renamed Orthonol by them.

An exact determination of  $\Delta B$  as discussed in Ref. (2) requires that the material actually be used in a rectifier to determine the maximum  $\Delta B$ . As a result, it is to a small extent a function of the ability of the contacts to open without arcing. In lieu of this, the value of  $\Delta B$  in the knee of the saturation curve can be used. The best estimate of the actual position is of course made from experience but you can go further up as you increase the number of turns in the main winding since the magnitude of the current is still low. Fig. 17.

Improvement of the materials having rectangular hysteresis loops was delayed until a method was developed to





measure the characteristics under conditions approximating actual service. A DC loop, which was the conventional method, gave only a relative indication and was of no use as a basis for the calculations. The oscilloscope method is only approximate. As a result, no real progress was made until the Vectormeter was developed by Koppelman. This is essentially a small single phase mechanical rectifier which integrates to give the values of  $\beta$  and  $H$  versus an electrical angle. A complete description of its theory of operation is given by Koppelman (6). The circuit diagrams, pictures, and circuit constants of the one used for this test are included with the necessary calculations in Appendix I. These units were designed to work at 50 cycles but are performing satisfactorily at 60 cycles in this country.



### 1. The Limitations imposed by Voltage and AC Source Inductance

The design of any rectifier must be based on the AC voltage available and the desired DC voltage. The AC voltage is normally transformed up, or down, to the necessary AC voltage to give the desired DC voltage. The maximum DC voltage available for any AC input is well known from mercury arc and selenium oxide rectifier design and applies equally well to the mechanical rectifier. Considering now only three phase input, the maximum DC voltage for a star pointed connection is  $1.17 E_\phi$ , and for a bridge connection, twice that or  $2.34 E_\phi$ , Fig. 11.

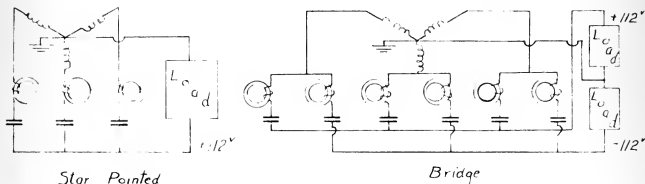


Fig. 11

If a star pointed connection is contemplated, the effect of residual magnetism resulting from unidirectional flow of AC current must be considered, unless some such system as a zig-zag connected transformer is contemplated. The bridge connection would have no such disadvantage unless it were connected to a 3 wire system with a load unbalance. This connection also of course has a ripple frequency twice



that of star pointed connections, making it easier to filter.

For purposes of this investigation, it was apparent that from a weight point of view, in particular, it would be advantageous if no transformers were required. It is readily apparent then, that with the AC voltage of 120/208 volts available, a no load voltage of either 140 or 280 volts is possible without transformers. And, considering regulation, a full load voltage of either 112 or 224 volts could be obtained. With these two considerations in mind, there are two immediate answers, either the conventional one wire 112 volt system presently being considered for aircraft or; a two wire 112/224 volt system with a neutral structural return. would appear to the author to be well worth considering. This is particularly true since the negative side would be a ready source of negative bias in electronic equipment.

A bridge connection is only two, star pointed systems, put together so that for the purposes of this investigation, it was thought best to use a star pointed system for the following reasons:

1. It is the simplest connection and lightest for a given power output.
2. It could give the DC voltage which is currently being considered for aircraft.
3. By simply combining two, it could be made into a bridge connection with double the power output and with no electrical redesign.



4. A large enough alternator would be used so that this unit would draw less than 15% of the rated power output. This should make the residual magnetism effect small; probably too small to be objectionable.
  5. The star pointed connection will have a greater overload capacity. This is true since the DC bus bars would be shorted out if both contacts were closed at the same time. (60 degree limitation)
- Fig. 10.

The line to line short circuit resistance of the AC supply system will affect the regulation of the rectifier. The AC transient analysis of an RL circuit, shows that the equation for the short circuit current is:  $i_s = \frac{e_c(t)}{X_L}$ . For any rectifier connection,  $e_c = E_c \sqrt{2} (1 - \cos \omega t)$ . ( $E_c = 208$ ) This can be readily seen by referring to Fig. 12. Therefore:

$$(1) \quad i_s = \frac{E_c \sqrt{2}}{X_{L_s}} (1 - \cos \omega t)$$

The actual value of  $\omega t$  will depend, of course, upon the value of load current, since commutation will be completed when  $\alpha_s = \alpha_L$  as was shown previously.

This time, however, also results in a reactive voltage drop as a result of the voltage area loss, as was shown in Fig. 2. The voltage area loss can be found by integration to be:

$$(2) \quad \int_0^t e_c dt = \frac{E_c \sqrt{2}}{\omega} (1 - \cos \omega t)$$





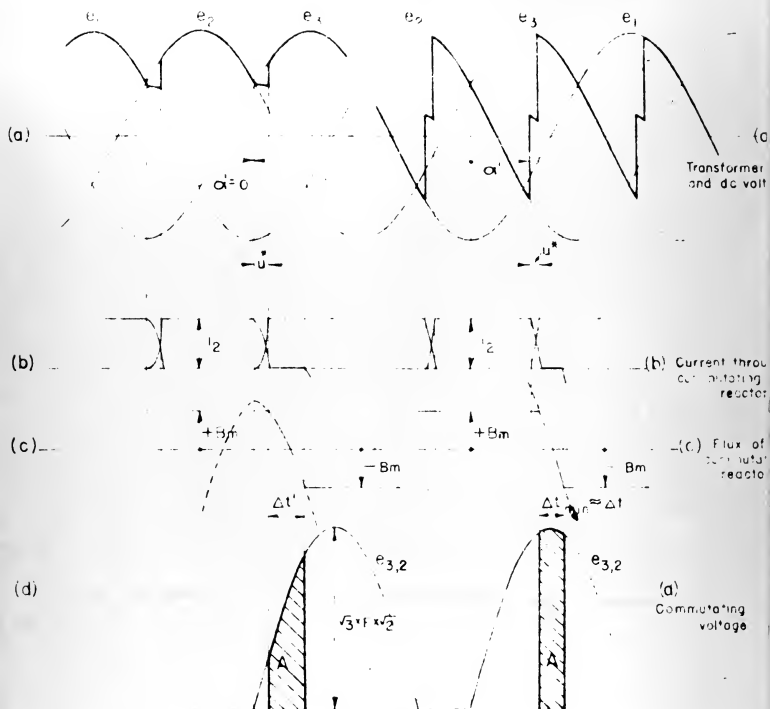
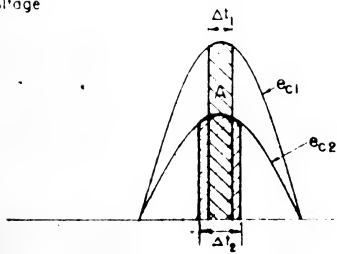


Fig 12

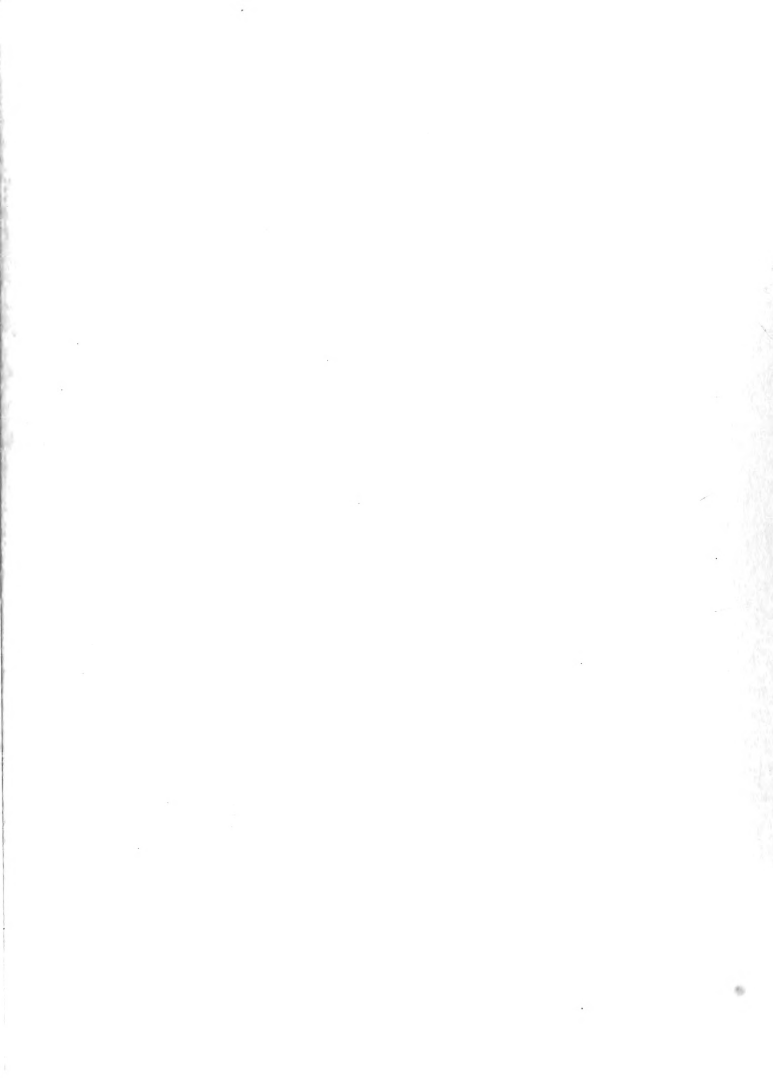




A consideration of Eqs. (1) and (2) will show that the lower the AC reactance, the larger the load current will be for a given output voltage, neglecting for the moment IR drop. The AC reactance then, is a definite limitation on the maximum power capacity.

It is now apparent that another reason for not using transformers is that the leakage reactance of the transformers will only add to the inductance of the system. For rectifiers working from a large power system, the transformer is the only source inductance which need be considered. However, for any system which will be used in aircraft in the foreseeable future, the short circuit reactance of the alternator will be a large part of the total system inductance.

The actual value of short circuit reactance which should be used, is a variable, depending upon the loading of the machine, since  $L = n \frac{d\phi}{di}$ . Of course the magnetic saturation curve gets flatter as the alternator is loaded up and the field current of necessity is increased. The Eclipse - Pioneer Division of The Bendix Aviation Corporation was kind enough to supply the calculated data on their 90 KVA alternator. The only reactance which is of interest in these calculations is the subtransient reactance. Rolf (3), Park and Robertson (5). This is true since the commutating time is .4 milliseconds at maximum overload. Unfortunately, all calculated data was computed on the basis of the air gap line (unsaturated). This would make the values used too large, just how much is a matter of



conjecture. In any event, to make this investigation conservative, the calculated value was used.

It can be easily seen from the limitations placed on the output DC voltage, that there is a maximum possible output capacity for a given AC source reactance. This can be varied to some extent by varying the inductance of the commutating cores main winding as will be seen in Chapter III. This is a fact which must be kept in mind as this paper is read, since it placed very definite limitations on the minimum weight of the cores.

There is also a minimum load for a mechanical rectifier. The load current must produce more ampere turns than does the pre-excitation. If this were not true, the step would occur at some unpredictable time. This would not necessarily be at the time that the contacts open. This would result then in a flash over. This minimum load will be called base load in this paper and will be discussed in more detail in Chapter IV.

## 2. Voltage Control

The two methods presently used for voltage regulation of a mechanical rectifier, neglecting a variable tap transformer, were discussed in the introduction. They accomplish the same thing, delay in the start of commutation. Some of the mechanical complexities of the mechanical system are readily apparent without dwelling further on the idea. The magnetic delay method is an easy system mechanically since the contacts continue operating as they did before. The disadvantage of such a system is that a more complex pre-excita-



tion system must be utilized and some compromise must be made with optimum pre-excitation. This is not a serious disadvantage, especially in small rectifiers with a large number of turns in the main winding. For a rectifier of this size, it is definitely a better system and so was used.

### 3. The Effect of Load Characteristics

Another consideration in determining whether a shift in contact closing time will be useful in reducing the size of the core is an evaluation of the load characteristics. A shift in opening time, will reduce the necessary step length of the breaking step since the opening time can be made to fall within the step by several methods, Fig. 13. However, this assumes that the load will change no faster than the contact closing time can be shifted. This is a poor assumption for any military installation. The resultant requirement for a long step length, merely increases the desirability of using the mechanical simplicity of magnetic delay.

It is possible, with all of the systems utilizing unidirectional current through the cores, to use only one core for both the make and break steps. This reduces the weight since it is not necessary to use a big make reactor too. The other system using bi-directional current and therefore two contacts for each core was not even considered in this investigation since the overload limitations are very severe, and magnetic delay cannot be used.





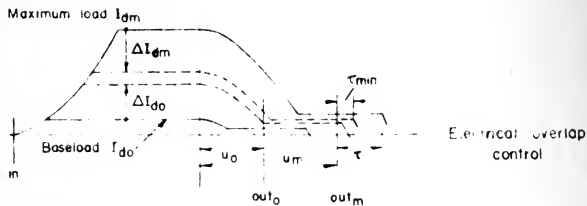
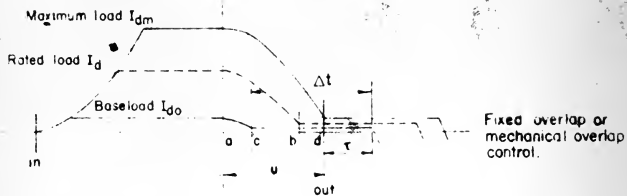
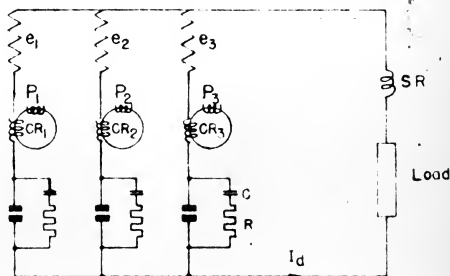


Fig 13



## CHAPTER III

### SELECTION OF A CORE

#### 1. Experimental Data

Reasonable assumptions on the saturable core characteristics had to be based on some sort of data. All quantitative information available in the literature, was for step lengths of 1 millisecond and longer and for ribbon thicknesses of .03 millimeters (1.2 mils) and thicker.

Dr. Rolf (3) gave some relative information on losses versus step length and ribbon thickness which is included in this report as Fig. 14. This information is for 5000Z but should closely approximate presents results using Orthonol.

This figure indicated that the thinnest ribbon currently available would be best to use for this investigation. The use of such thin ribbon results in other problems. The primary difficulty is the actual rolling of the ribbon and the winding of the core. Another adverse factor is the decrease in the maximum flux density for saturation as the ribbon is made thinner. There is some reason to believe at the present time that this may be the effect of surface impurities. That is merely conjecture, however, and any confirmation will require more investigation. If this be true, current research by NOL on saturable cores may solve this problem. In this case, improvement for use in magnetic amplifier applications also means improvement for use in a mechanical rectifier.



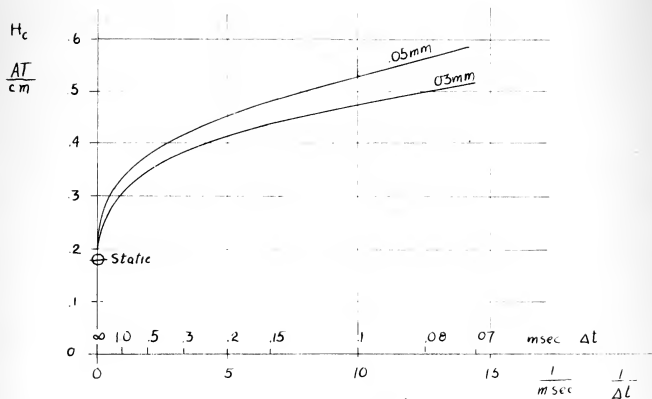
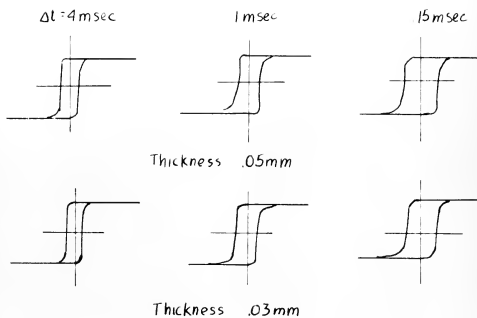


Fig-14



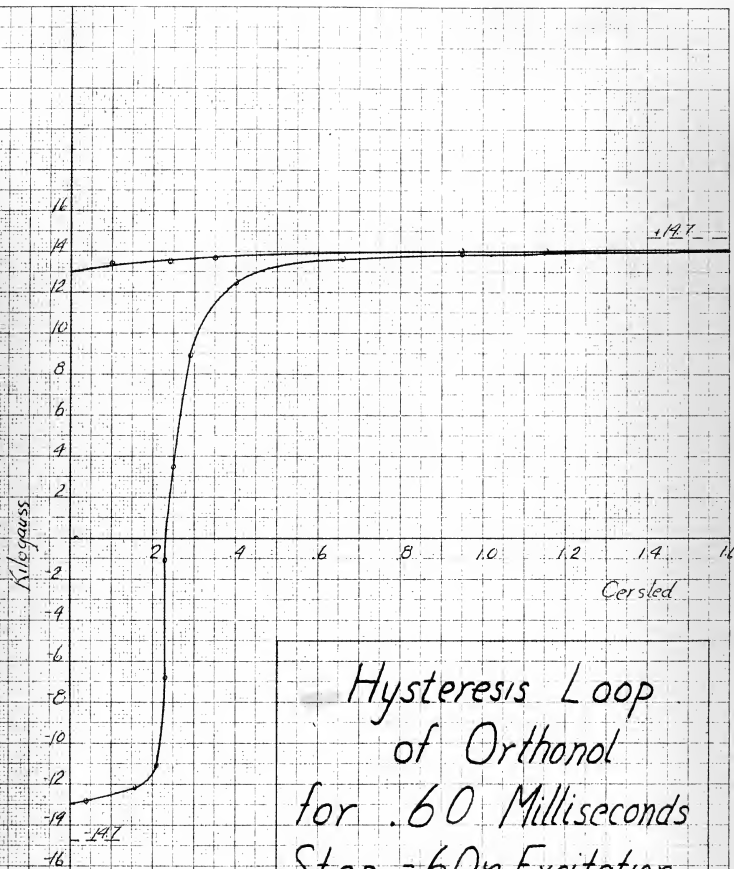
The Vectormeter appeared to be the only method to obtain accurate quantitative data. The data obtained from this unit at 60 cycles could be used as a reference to obtain the hysteresis loop for 400 cycles by comparing the two under identical conditions. The methods used in this paper gave hysteresis plus eddy current losses, even though they will be referred to as hysteresis loops throughout this paper. This was especially attractive since it was anticipated that there would be little difference between the loops for the two frequencies for a given step length. The results are shown in Figs. 15, 16, 17, and 18.

It was anticipated that the eventual design step length would be between .6 and .3 milliseconds and so the comparisons were made at those frequencies. The circuit used is shown in Appendix I.

The experimental core furnished by the Magnetic Amplifier Section of NOL consisted of 190 turns of Orthonol ribbon .0006" x .25". It had its final heat treatment in a constant magnetic field of 87.2 oersteds at 200°C. This was the only variation from the method described by Jensen (1). The DC loop shown in Fig. 19 was obtained with the conventional ballistic galvanometer method by NOL personnel. The hysteresis loops for approximately 1.2 and .2 milliseconds are given in Appendix I. The loop for a .2 milliseconds is only approximate. It appears to be about the shortest step length for which this model Vectormeter can be used. Periodic difficulties were encountered during the actual operation as a result of fluctuations in the line







Hysteresis Loop  
of Orthonol  
for .60 Milliseconds  
Step -60<sup>u</sup> Excitation

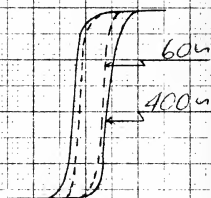
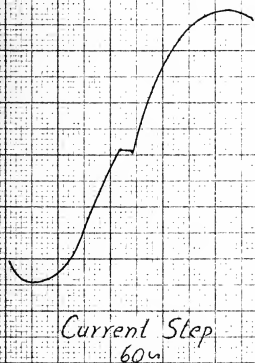
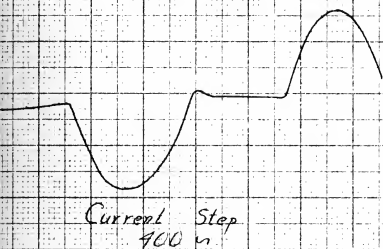
NOL 2-50

G.L.B

$$\Delta T = \frac{96.5 - 83.5}{21.6} = .60 \text{ msec}$$

Fig. 15





Hysteresis Loop

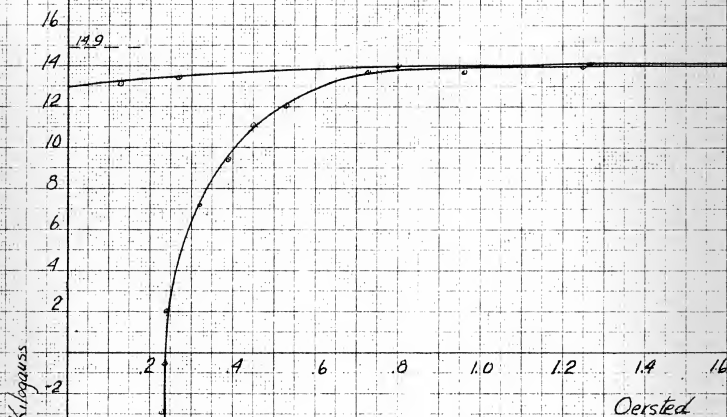
Effect of Frequency  
on the  
Hysteresis Loop of Orthonal  
for a

Step Length of .6 millisecond

NOL 2-50

GLP





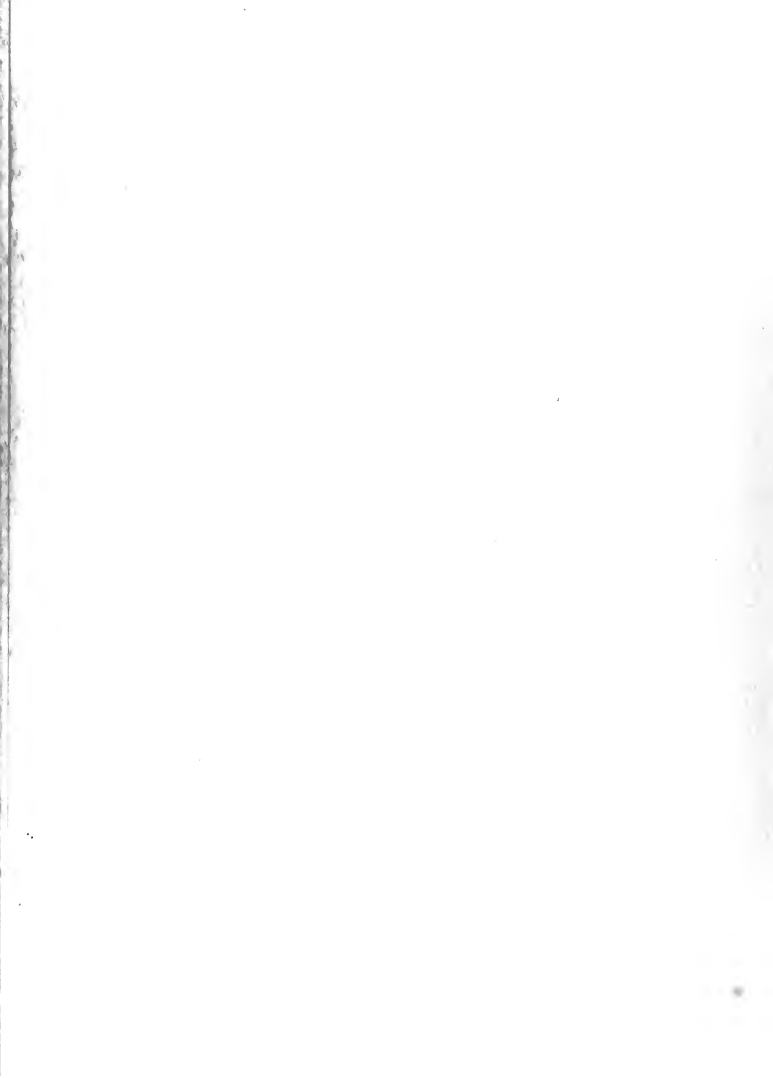
Hysteresis Loop  
of Orthonol  
for .33 Milliseconds  
Step 60<sup>u</sup> Excitation

NOL 4-50

GLB

$$\Delta T = \frac{93.0 - 85.8}{21.6} = .33 \text{ msec}$$

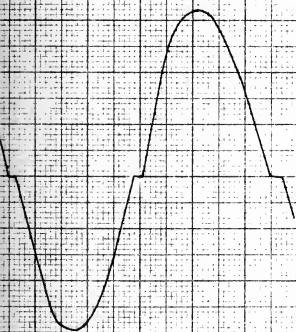
Fig. 17





Current Step -  $400 \mu s$

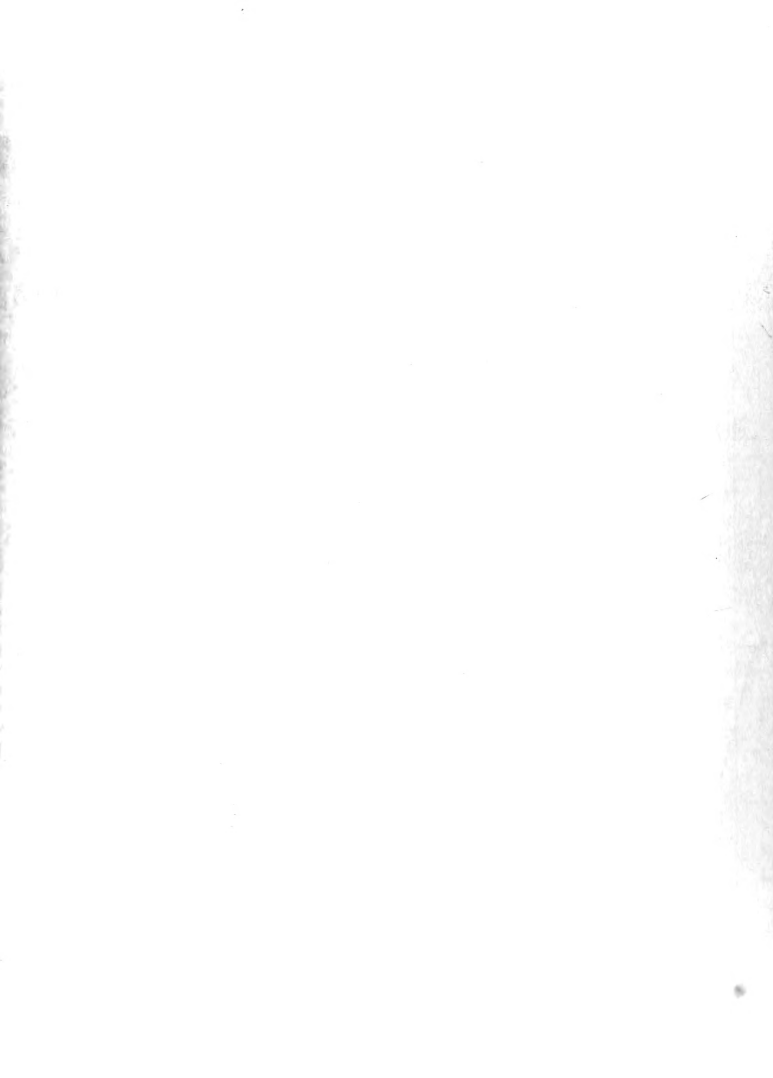
Hysteresis Loop



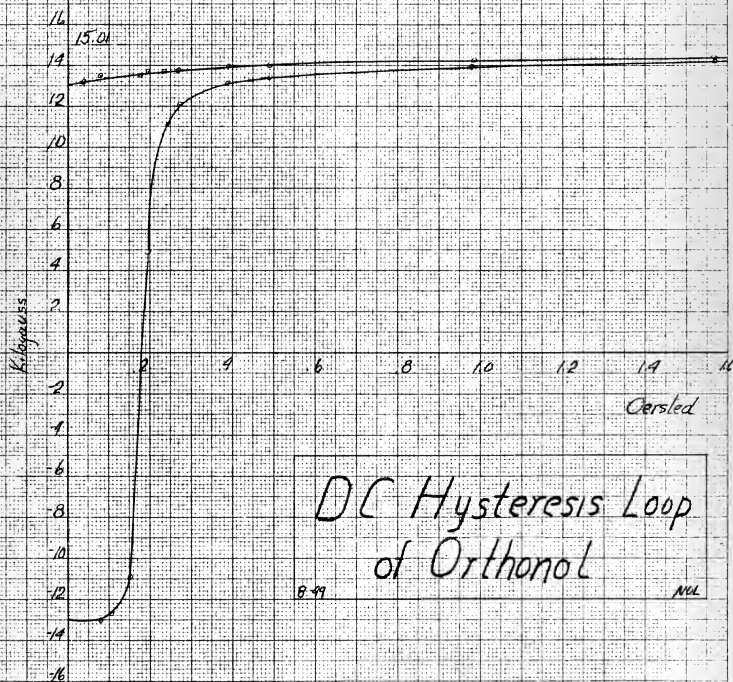
Current Step  $60 \mu s$

Effect of Frequency  
on the  
Hysteresis Loop of Orthond  
for a  
Step Length of 30 Milliseconds  
NOL 4-50 GLB

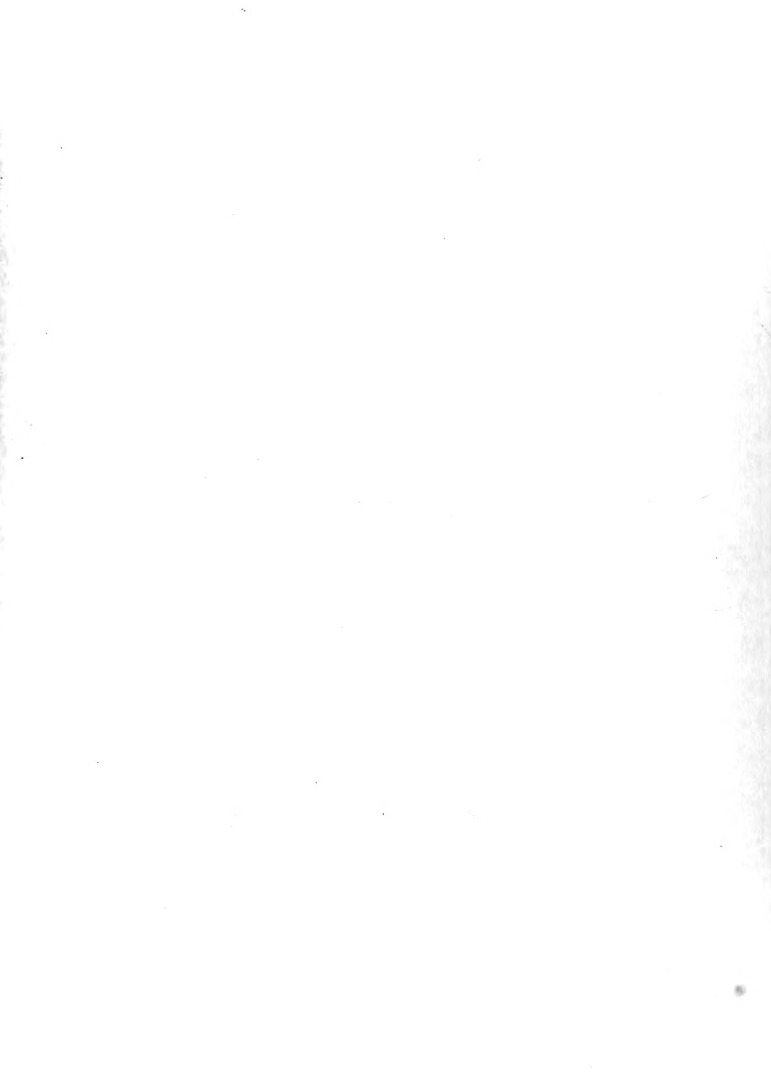
Fig 18







DC Hysteresis Loop  
of Orthanol



voltage but beyond that, no difficulty was encountered.

A  $\Delta B$  of 26 kilogauss was selected from the data obtained. This may appear a little optimistic on the basis of the loops actually obtained. However, the saturation value was about .4 kilogauss lower than would normally be expected on the basis of data on other cores. This is of no great concern since any overestimate would only result in a slightly optimistic figure for overload. The error certainly is not more than 2 kilogauss or 8%. This could be easily more than counterbalanced by the overestimate in the reactance of the alternator.

The determination of the required step length at this point in the investigation is at best, a shot in the dark. There are several formulae available in different forms for this calculation. The one developed by Loppelman (2) in his original series of articles on the subject seems the best to this author. This is particularly true since it emphasizes the factors which influence the required step length, and so the weight, power output, and all of the other factors considered previously.

A photostat of the pertinent part of this series, showing the derivation of the step length formula, is included as Appendix II to this report.

## 2. The Determination of Probable Step Length.

A study of the characteristics which this rectifier will probably have shows that the critical loads will be rated load and maximum overload. This is undoubtedly not apparently to the reader unless he has had considerable



experience with these units. However, a little thought will show that up to rated load, there is some voltage control. This will cause a delay in the start of commutation, and as a result, a delay in the start of the step. Considering now IR drop, the difference in voltage area used up for commutation at rated load and that used up for voltage control and commutation at any lower load will be the additional IR drop, if the output voltage at the two loads is the same. For that reason, the step will start sooner at rated load than at any other load. This assumes of course that the rectifier has been designed so that it will just deliver rated voltage at rated current. If the design is too conservative, the critical load will be at some overload value and for an optimistic design, at a value below rated load current. In the latter event, the rating of the unit would have to be reduced.

The following is a preliminary evaluation of the required step length, using Koppelman's formula for step length.

$$\text{From Eq. (1)} \quad i_s = \frac{E_c \sqrt{2}}{X_{Ls}} (1 - \cos \omega t)$$

This becomes, for rated load

$$X_{Ls} = \frac{E_c \sqrt{2}}{I_L} (1 - \cos \omega t)$$

Also, from Eq. (2)

$$\int_0^t e_c dt = \frac{E_c \sqrt{2}}{\omega} (1 - \cos \omega t)$$



Substituting the value of  $X_{L_s}$  to obtain rated voltage at rated load, the maximum value can be shown to be:

$$X_{L_s} \leq \frac{\omega \int_0^t e_c dt}{I_r}$$

or:

$$(3) L_s \leq \frac{\int_0^t e_c dt}{I_r}$$

By integration, the total voltage area for one cycle, assuming no voltage loss from commutation or delay, is:

$$E_\phi \sqrt{2} \int_{30}^{120} \sin \omega t dt = \frac{E_\phi \sqrt{6}}{\omega} = \frac{120 \sqrt{6}}{800 \pi} = .117 \text{ volt secs.}$$

This is equivalent to 140.4 volts DC.

$$\text{Voltage} = \frac{.117 \times \omega}{\frac{2\pi}{3}} = \frac{.117 \times 800 \pi}{\frac{2\pi}{3}} = .117 \times 1200 = 140.4$$

Considering now the rated load voltage, 115 volts in this case, there is a definite amount of voltage area which can be used up in commutation. Also some allowance must be made for IR drop. For a unit of this size, with a current density of about 125 circular mils per ampere, a reasonable estimate of IR drop is 4 volts. Therefore, the reactive voltage drop must be not more than:

$$140 - (115 + 4) = 21 \text{ volts}$$

This represents a voltage area of:

$$\frac{21}{140.4} \times .117 = .01756 \text{ volt secs.}$$





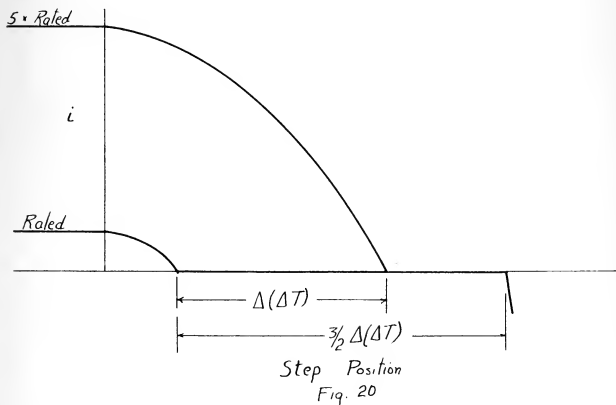
Using Eq. (3) and knowing that  $I_1 = \frac{9,600}{115} = 83.5^a$

$$L_s \leq \frac{.01756}{83.5} = 210 \mu h$$

Looking at the hysteresis loop, the core is not completely saturated until the mmf is about 20 oersteds. Therefore, there will be a finite delay resulting from this  $\Delta \beta$ . The actual voltage area can be computed by a method which will be shown later. This proves to be equal to .00656 volt seconds. This then places a maximum limit on L of:

$$L_s \leq \frac{.01756 - .00656}{83.5} = 132 \mu h$$

Koppelman's formula must be modified slightly to be used with the reasoning advanced at the beginning of this section. Fig. 20 shows the time actually obtained by this method:





Koppelman's original formula was:

$$\Delta T = \frac{\mathcal{E} U}{\omega(1 - \sigma - \gamma - \delta)}$$

$$\mathcal{E} = \frac{\omega L_s I_r}{E_c \sqrt{2}} = \frac{800 \pi \times 152 \times 10^{-6} \times 83.5}{208 \sqrt{2}} = .0941$$

$$\gamma = \frac{2(\beta_{max} - \beta_{in})}{\Delta \beta} = \frac{2(1.50 - 1.30) \times 10^{-4}}{2.6 \times 10^{-4}} = .0146 \text{ (Saturation Delay)}$$

$$\sigma = \frac{\Delta \beta_{out} - \Delta \beta_c}{\Delta \beta} = .33 \text{ by assumption (safety step)}$$

$$\delta = \frac{(\beta_{Rated Load} - \beta_{Base Load})}{\Delta \beta} = \text{negligible using Orthonol}$$

$U$  - over load factor (1 at rated load)

Referring again to Fig. 20, the safety step is of interest only for the minimum commutating time; this is the normal rated load in this case. The saturation delay of course enters into both considerations since it delays commutation under all conditions. The value of  $\Delta(\Delta T)$  then becomes:

$$(4) \quad \Delta(\Delta T) = \frac{\mathcal{E}}{\omega(1 - \delta)} \left\{ U_{max Load} - U_{rated load} \right\}$$



The value for maximum load rating was increased 25% to take care of manufacturing discrepancies, frequency shifts, voltage fluctuations, any over estimate of  $\Delta\beta$ , and an over simplification of a complex problem. This then gives a value for  $\Delta(\Delta T)$  of:

$$\Delta(\Delta T) = \frac{.0941}{800 \pi (1-.0146)} \left\{ 5 \times 1.25 - 1 \right\} = .199 \text{ milliseconds}$$

$$\text{Therefore } \frac{3}{2} \Delta(\Delta T) = .299 \text{ milliseconds}$$

For this investigation, .305 milliseconds was used.

From Jensen (1)

$$NA_{Fe} = \frac{\Delta T E_c \sqrt{2}}{\Delta \beta} = \frac{.305 \times 294}{2.6 \times 10^{-4}} = 346$$

Final calculations using this value gave an overload rating of 5.90 x rated current or 18% instead of the 25% originally designed for. This method appears to give a very accurate and simple method of rapidly computing the value of  $NA_{Fe}$ .

It is now possible to show the method which was used to determine the voltage area resulting from the saturation delay. Since we know the value of  $\Delta\beta$  and  $NA_{Fe}$ , the following formula can be derived:

$$e = N \frac{d\phi}{dt} \quad \text{or} \quad \int_{t_1}^{t_2} e dt = N \times (\phi_2 - \phi_1) \\ = N \times A(\beta_2 - \beta_1)$$

$$(5) \quad \int_{t_1}^{t_2} e dt = NA_{Fe} \Delta\beta$$

$$= 346 \times .19 \times 10^{-4} = .00656 \text{ volt secs.}$$



This then gives the voltage area which was used in the step length calculations. The remaining  $\Delta\beta$  of  $.01 \times 10^{-4}$  will be taken care of by another circuit.

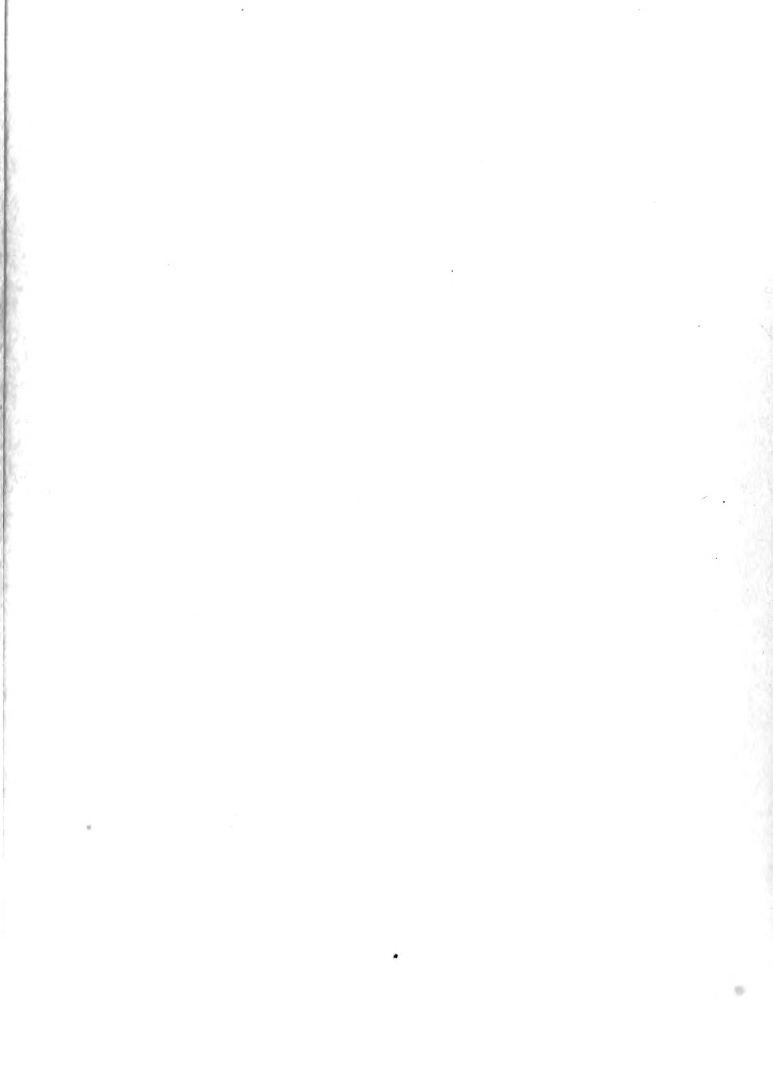
### 3. The Determination of the Optimum Core Area

The preceeding analysis gave an excellent starting point for the actual determination of the optimum core area, since one variable,  $NA_{Fe}$  has been eliminated from the calculations. There are, of course, an infinite number of combinations which will give this product. However, the design output voltage is still the determining factor. This then limits the maximum inductance of the entire short circuit path.

This limitation immediately suggests that we first consider the reactance over which there is no control. This is the inductance of the source. One of the initial conditions imposed was that there would be no transformer used. The rectifier will probably be mounted next to the alternator so that the source reactance, is the reactance of the alternator. This reactance is the subtransient reactance as was discussed in Chapter II. The value supplied by Eclipse for their 90 KVA alternator was 33% for the direct and quadrature axis (unsaturated) at 320 cycles. Using the method advanced by Park and Robertson (4), the following results were obtained:

$$\text{Normal ohms} = \frac{\text{normal line to neutral voltage}}{\text{normal line current}}$$

$$= \frac{208}{13} \times \frac{208 \sqrt{3}}{90 \times 10^3} = .48 \Omega$$





Subtransient reactance = 33% at 320

$$= .33 \times .461 = .159 \text{ at } 320 \sim$$

$$\text{Therefore } L_a = \frac{.159}{\omega} = \frac{.159}{2\pi 320} = 79 \mu h$$

This means then that the maximum inductance of the main winding of one core  $\leq \frac{152-79}{2} = 26.5 \mu h$

We now know the maximum allowable inductance of the main winding, the value of  $NA_{Fe}$ , and the only other limiting factor is the value of  $\frac{2W}{d_m}$  (Fig. 21). Gaugler (5) has shown that the slope of the side of the hysteresis loop decreases as the value of  $\frac{2W}{d_m}$  increases. This slope can be represented by the relation:

$$\Delta H_m = H_c \ln \frac{r_o}{r_i} \quad \text{Fig. 22}$$

The optimum value of  $\frac{2W}{d_m}$  is a complete problem in itself. For this investigation, the same value was used as was used in the sample core to insure reasonable results, 0.414. It was a reasonable value, however. Dr. Rolf (3) stated that the value varied from 0.25 to 0.45 in German rectifiers and from 0.4 to 0.65 in the rectifiers built so far in this country. A larger value would have meant a lighter core at the sacrifice of slope.

The only other factor needed was stacking factor. It was very low as a result of the thin ribbon used. Again, the value obtained from the sample core was used, 0.340.



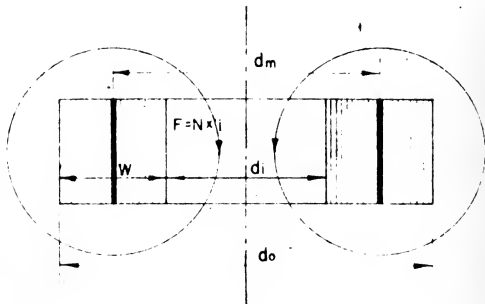


Fig- 21

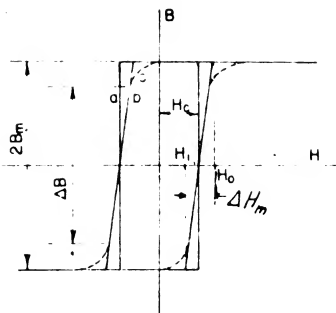


Fig-22



The final attempt to insure that the core would have the same characteristics as the sample was made by making the core up out of layers of individual cores the same height as the sample core,  $\frac{1}{4}$  inch. This introduces problems in matching which will be primarily production problems. The effects of poor matching will be discussed later. It may well be necessary, however, to use these thin sections with the short step lengths used, to reduce the effect of eddy currents on the size of the hysteresis loop.

All of these boundary conditions were combined as a basis for calculations which resulted in Fig. 23. As an example of the method used, the calculations for the core finally selected are as follows:

$$A_{Fe} = \frac{346}{70} = 4.95 \text{ sq. cms.}$$

$$A_{core} = \frac{4.95}{.340} = 14.6 \text{ sq. cms.}$$

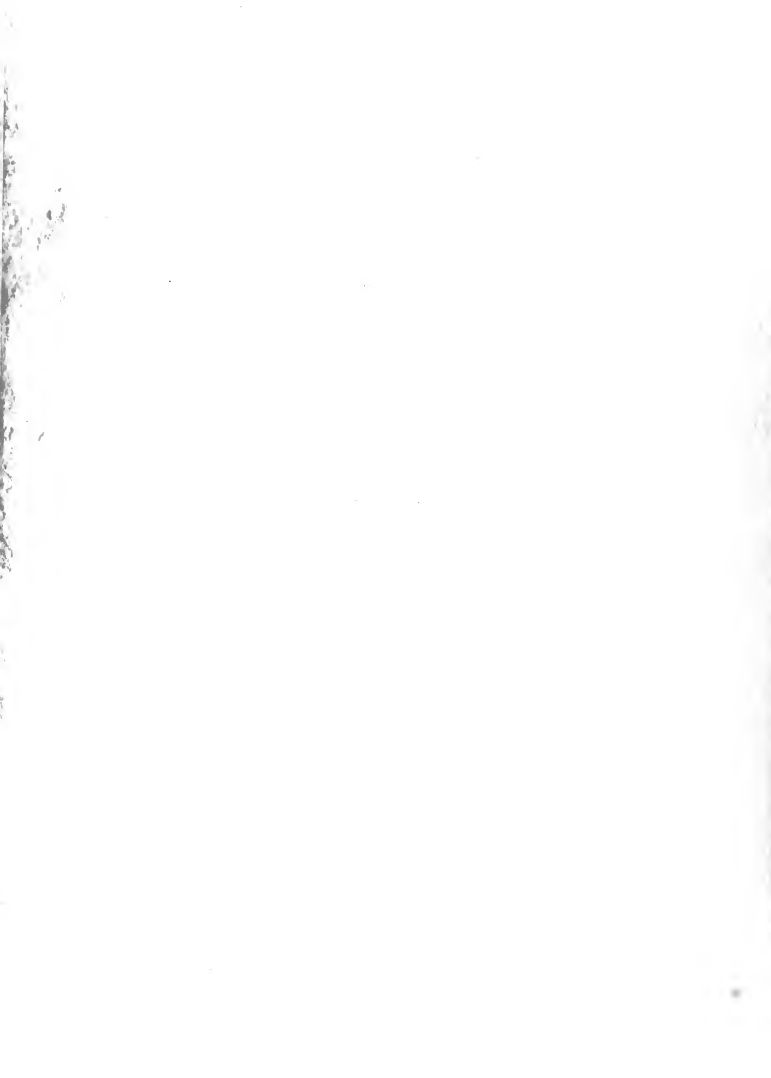
$$\text{Height} = 7 \times \frac{1}{4} = 1.75 \text{ in. or } 4.45 \text{ cms.}$$

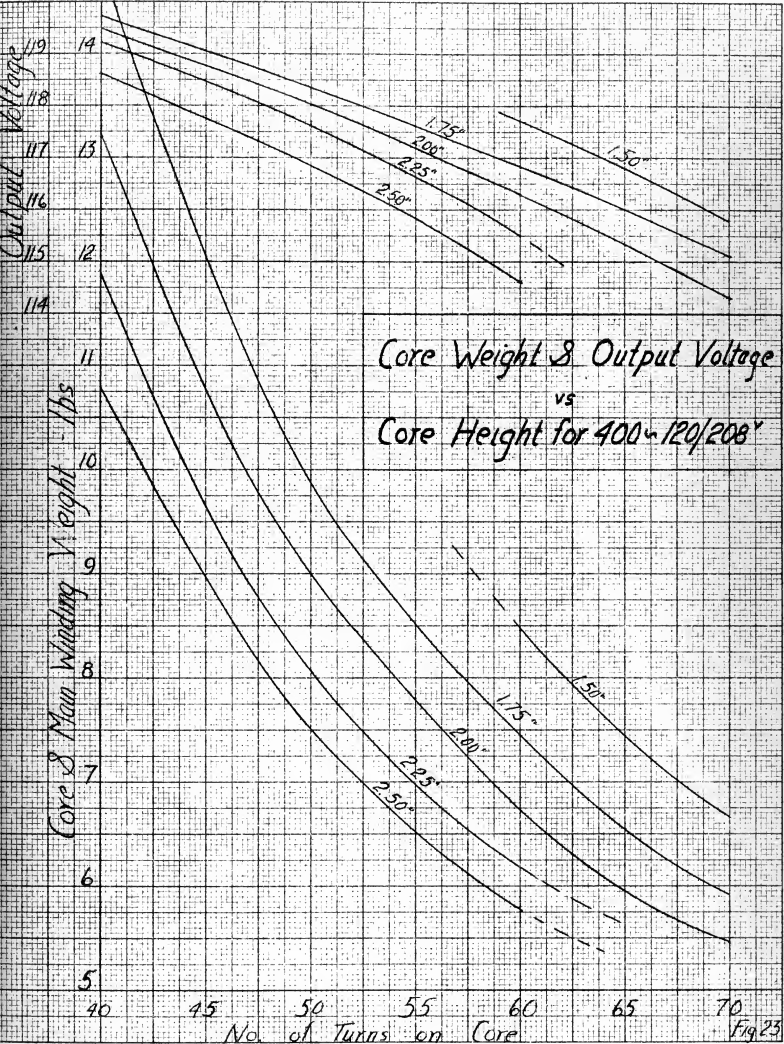
$$\text{Thickness} = \frac{14.6}{4.45} = 3.28 \text{ cms.}$$

$$d_m = \frac{2 \times 3.28}{.914} = 7.19 \text{ cms.}$$

$$OD = 15.85 + 3.85 = 19.7 \text{ cms or } 7.76 \text{ inches.}$$

The calculation of the inductance of the main winding required that the area enclosed by one turn be determined. For this, a spacing of .15 cms. was allowed for each









individual layer for potting, supports, and outside insulation. The radius of the copper of the winding was neglected since it was small as compared with the assumptions for the spacing.

$$A_t = (4.15 + 7 \times .15)(3.28 + 2 \times .15) = 19.7 \text{ cms.}^2$$

Dr. Rolf (3) recommended that the theoretical air core induction for a torodial core be multiplied by a factor of 1.05 so that the difference in spacing between the turns on the inside and outside of the core would be considered. The air core induction was used since the effect of the iron core is negligible during commutation. (  $\delta = 0$  )  
The formula then becomes:

$$L = \frac{4.2 N^2 A_t}{d_m} = \frac{4.2 (70)^2 \times 19.7}{15.85} = 25.6 \mu h$$

$$\text{Therefore } L_s = 79 + 2 \times 25.6 = 130.2 \mu h$$

And from Eq. (3)

$$\int_0^t e_c dt = I_s L_s = 83.5 \times 130.2 \times 10^{-6} = .01088 \text{ volt secs.}$$

The voltage area for the saturation delay was: .00656 volt seconds.

Therefore the net voltage area was:

$$.117 - (.01088 + .00656) = .09956 \text{ volt secs.}$$

This gives a reactive voltage of:

$$.09956 \times \frac{\omega}{3} = .09956 \times 1200 = 119.6 \text{ volts}$$



The core weight can also be determined, again using the test core.

$$\frac{4.95}{.205} \times 24.4505 \times 2.205 \times 10^{-3} \times \pi \times \frac{15.85}{14.46} = 4.50 \text{ lbs.}$$

The core loss can be determined directly from the hysteresis loop area. The hysteresis loop for .30 milliseconds was used for the calculations. Actually, the step will never be quite that short since the commutating voltage will never be an average of  $E/2$  as was assumed in obtaining this value. However, this will give a conservative answer.

Area of hysteresis loop  $= \int B dH$  for  $B$  in gauss and  $H$  in  $A/cm$ , and  $\rho$  in grams/sq. cm.

$$a = \int B dH = \frac{10^8 V \text{ sec}}{cm^2} \times \frac{AT}{cm} = \frac{10^8 \text{ Watt sec}}{cm^3} \quad \text{or} \quad W = a \times 10^{-8}$$

This will give a loss per gram of:

$$\text{Loss/gram} = \frac{W \text{ sec}}{cm^3} \times \frac{1}{\text{sec}} \times \frac{cm^3}{g} = \frac{W}{g} = \frac{a \times \text{freq}}{\rho} \times 10^{-8}$$

$$(b) \text{ Loss/lb.} = \frac{a \times \text{freq} \times 10^{-8}}{\rho \times 2.205 \times 10^{-3}}$$

The .30 millisecond step at 60 cycles (Fig. 17) has a value of  $a = 30,600 \frac{W \text{ sec}}{cm^3}$ . Fig. 18 shows that the ratio of areas is 1.2. Therefore the area for 400 cycles for a .30 millisecond step is:



$$50.6 \times 10^3 \cdot .12 = 36.8 \times 10^3 \frac{Wsec}{cm^2}$$

$$\text{Therefore } W/lb. = \frac{36.8 \times 10^3 \times 400 \times 10^{-8}}{8.25 \times 2205 \times 10^{-3}} = 8.1 \text{ watts / lb.}$$

And the core loss is  $8.1 \times 4.50 = \underline{36.4}$  watts.

Returning now to the main winding copper. If a current density of 125 circular mils per ampere is used, this gives a cross sectional area of  $125 \times 83.5 = 10,430$  circular mils. Number 10 gage wire has a cross sectional area of 10,400 circular mils, therefore this was selected for the main winding. The Bureau of Standards Circular #31 lists the following physical constants for #10 wire:

Resistance = 1.18 ohms/1000 ft at 65° C.

Weight = 31.47 pounds/1000 feet

Allowing 48 inches for external connections, the copper length will be, neglecting advance per turn:

$$\frac{(2 \times 5.50 + 2 \times 3.50) \times 70 + 48}{2.54} = 548 \text{ inches}$$

$$\text{Copper weight} = \frac{548 \times 31.47}{1000 \times 12} = 1.44 \text{ pounds}$$

$$\text{IR drop} = \frac{548 \times 1.18 \times 83.5}{1000 \times 12} = 4.48 \text{ volts}$$

$$I^2R = 4.48 \times 83.5 = 376 \text{ watts for } 120^\circ \text{ out of } 360^\circ.$$

Therefore, average  $I^2R = 125$  watts.

#### 4. Final calculation of step location and length.

Now that all of the characteristics of the core are known, it is possible to determine where the step will be located for any load. This will make it possible to



calculate how much overlap there should be and what the maximum overload will be. Effects of frequency and voltage fluctuations can also be determined.

The following is a sample calculation to show how the data for Fig. 24 was calculated.

Load - 1 rated

$I = 41.7$  amps.

IR drop =  $.0538 \times 41.7 = 2.24$  volts

Reactive voltage =  $115 + 2.24 = 117.24$  volts

Voltage area for 115 volts =  $\frac{.117 \times 117.24}{140} = .0980$  Volt secs.

Reactive voltage area drop =  $.117 - .0980 = .019$  volt secs.

Voltage area to saturate core =  $.00656$  volt secs.

Commutation voltage area =  $41.4 \times 130.2 \times 10^{-6} = .00538$   
volt secs.

Voltage area for magnetic delay =  $.019 - (.00656 + .00538)$   
 $= .00706$  volt secs.

From Eq. (2)

$$\cos \omega t = 1 - \frac{\omega \int e_a dt}{E_c \sqrt{2}} = 1 - \frac{800 \pi \times .00706}{294}$$

$$\omega t = 2 \cdot 20.1^\circ$$

Therefore, the make step will last  $20.1^\circ$  after the contact has closed.

The current will complete commutation after:

$$\cos \omega t = 1 - \frac{800 \pi \times .019}{294}$$

$$\omega t = 33.2^\circ$$

$33.2^\circ$  after the contact has closed.



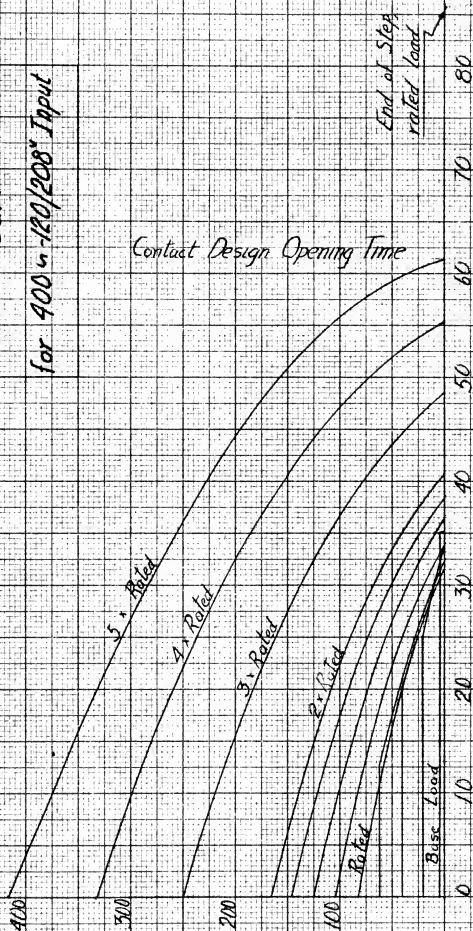


# Commutation Time vs Load Current

for 400 ~ 120/208" Input

Contact Design Opening Time

End of Stop  
rated load



DC Amps. - Load Current

Degrees  
Commutation Time

Fig 24



This angle also determines when the decay is completed and the break step starts. Therefore, the break step will start  $120 + 33.2^\circ$  or  $153.3^\circ$  after the contact closed.

The equivalent voltage area of the break step can be calculated by Eq. (5)

$$\int e dt = N A_{Fe} \Delta B = 346 \times 2.6 \times 10^{-4} = .0900$$

$$\text{Therefore: } \cos \omega t = \cos 32.2^\circ - \frac{800 \times .0900}{294}$$

$$\omega t = 86.5^\circ$$

Therefore, the break step will last until  $(120 + 86.5)$  or  $206.5^\circ$  after the contact closes. The values for the other loads are shown in Fig. 24. This shows that the maximum load this rectifier can carry without moving into the safety step is: 5.90 rated current.

Fig. 24 shows that the critical load is rated load as was predicted early in this Chapter. This load was used then to determine the proper overlap setting. Allowing a safety step of 1/3rd the total step, the contact must be set to open at  $67.5^\circ$  overlap or  $187.5^\circ$  after the contact closed. However, the contacts should be set for  $61.3^\circ$  or 5 times rated current. This will make the unit less sensitive to overvoltage and under frequency fluctuations.

Fig. 25 is a plot of output voltage versus load current. As can be seen, the mechanical rectifier is largely self limiting.

##### 5. The Effect of Frequency and Voltage Fluctuations.

The design thus far has assumed a constant frequency of 400 cycles and a constant input voltage of 120/208 volts



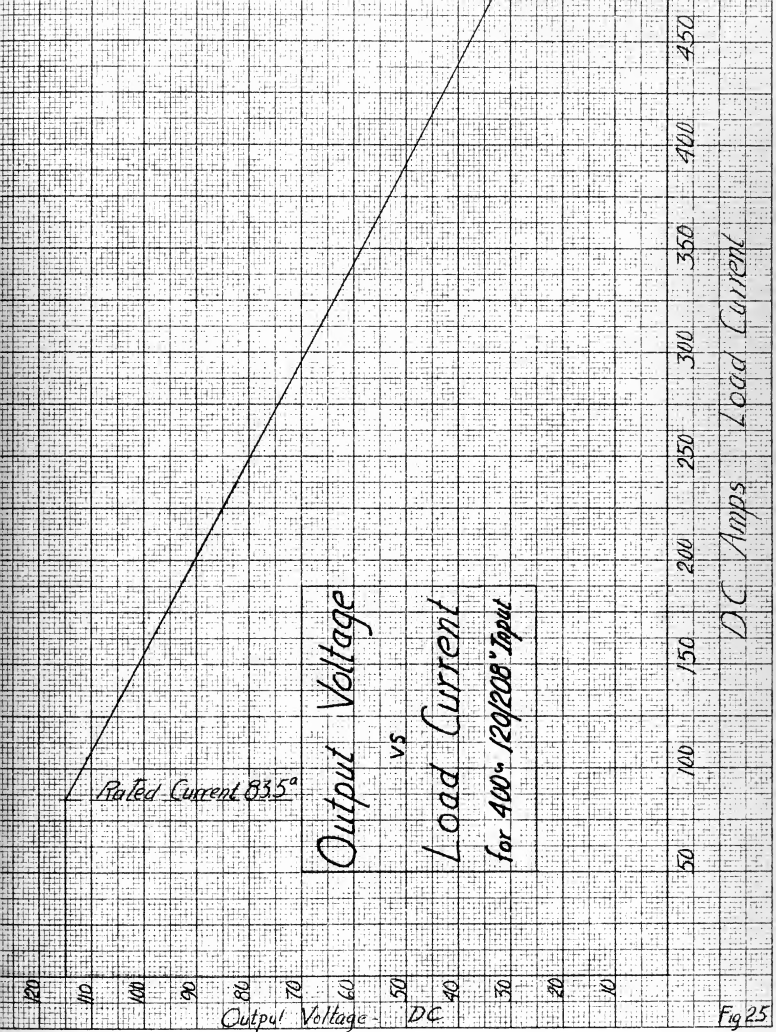


Fig 25



AC. Aircraft installations in particular cannot be expected to maintain any frequency or voltage exactly, no matter what sort of drive is contemplated.

There are several different frequency ranges now in the specifications. The most limited of these is the range of from 380 to 420 cycles for the constant speed drive. Considering this range first. An analysis in the same manner as was done for 400 cycles but only for the critical values shows that a rectifier with this long a step length has surprising flexibility.

380 cycles - Output voltage - maintained to 105%  
rated load

Maximum overload - Increased about 5%

This results since there is more voltage area and so the unit can carry more current before the reactive voltage drops to the minimum allowable value. Also, for maximum overload, there is more time for commutation. By the same reasoning:

420 cycles - Output voltage - maintained to 95% rated  
load

Maximum overload - reduced about 5%.

If we now try to put this rectifier on any engine driven alternator and assume that some one has designed a contact mechanism which will actually work at 930 cycles:

320 cycles - Output voltage - maintained to 125% rated  
load

Maximum overload - 170% of 400 cycles value





930 cycles - Output voltage - maintained to 80% rated  
load

Maximum overload - 175% rated load

Voltage at this rating

only 61 Volts, however.

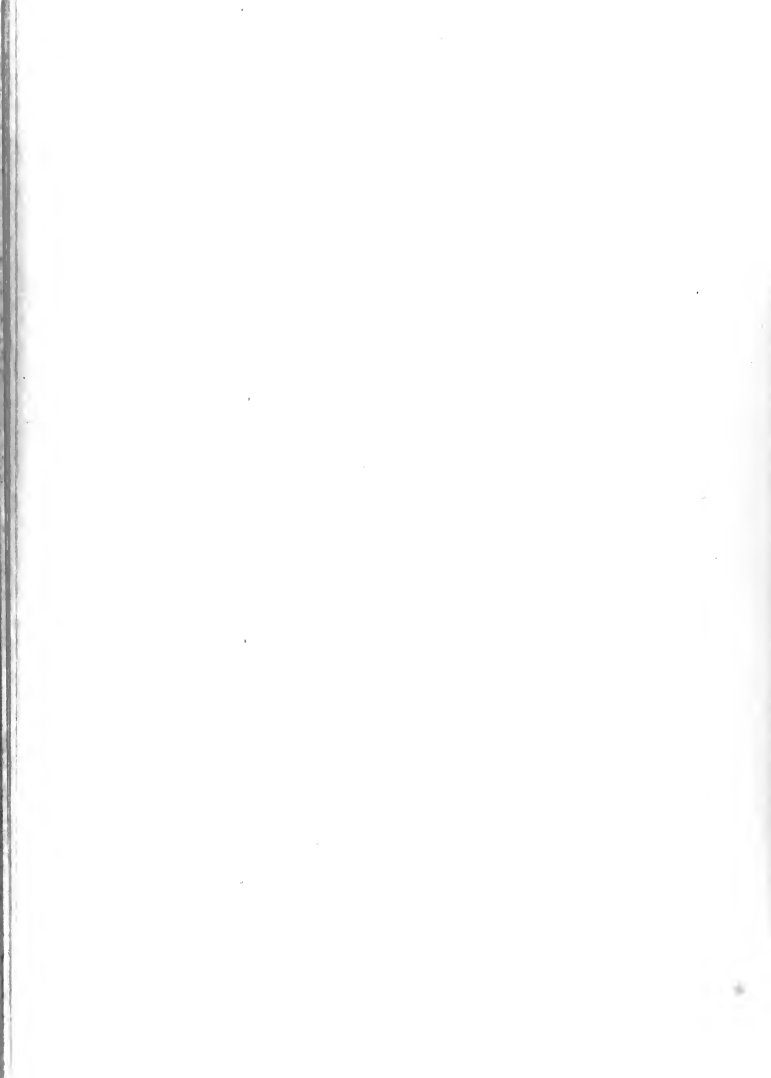
Now considering the effects of voltage fluctuations at 400 cycles, only, since other values could be readily obtained. Assuming a phase voltage of 150 volts, the critical load will be in the normal operating range, but the safety step will be reduced, however,  $t_k$  will still be  $9 \times 10^{-5}$  seconds for 67.5° overlap which is more than the minimum specified by Koppelman (2). This should only be a transient condition anyhow. This condition can be improved still more if the overlap is reduced to 61.3° or the equivalent of 5 x rated current at 400 *cyc/k*.

Assuming now a phase voltage of 80 volts, the critical load will exist in the overload region. At this voltage, the overload will be limited to 300% rated load. However, the output DC voltage for such a condition would be only 15 volts anyhow.

This has not been a complete analysis of the effect of transients on the performance of this rectifier; it should give an indication of the flexibility possible with this size core.

#### 5. Manufacturing and Handling Problems:

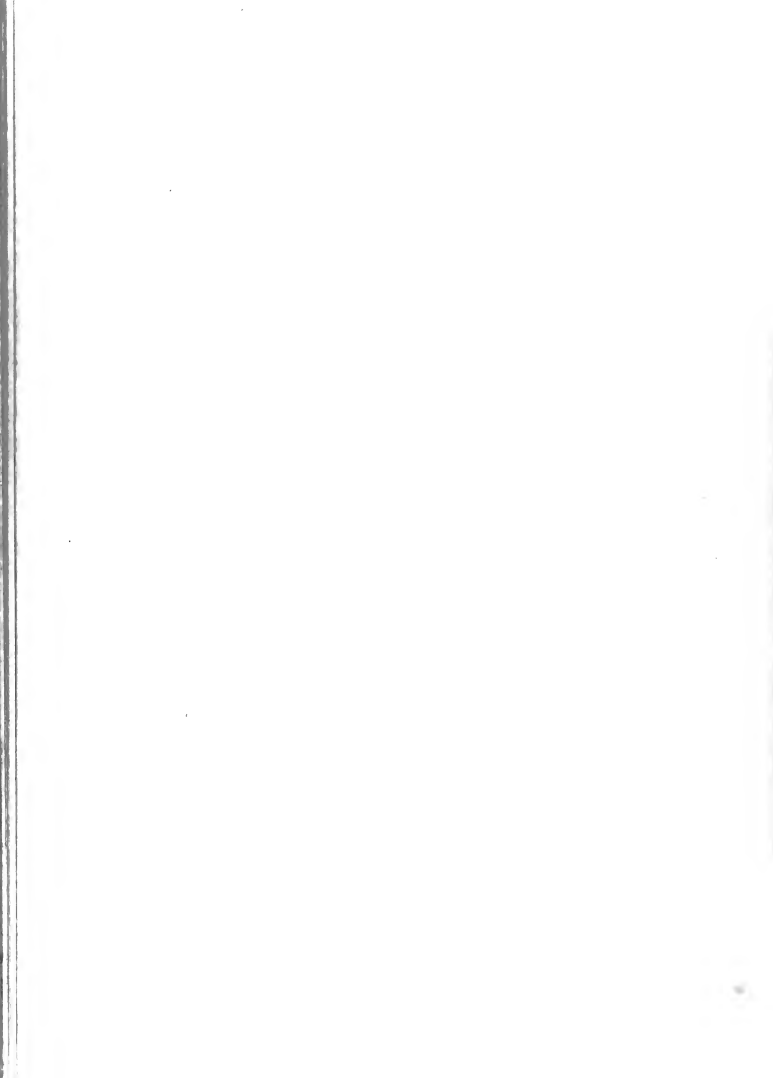
Before leaving the subject of saturable cores, it would probably be wise to mention some of the problems which are currently disadvantages and some which will probably always



be a disadvantage.

Any core which is made up of a number of individual ones such as this design envisions will be a severe production problem since they must all have almost the same size hysteresis loop to avoid a composite loop looking like Fig. 26. This is a severe handicap at the present time since there is no assurance just what size loop a given core will have until it is tested on the Vectormeter. This can probably be overcome by more careful control after more has been learned about the heat treatment.

It is also extremely important that the core be subjected to no physical stress. If the elastic limit is exceeded, the magnetic qualities will be ruined and the core will have to be junked. Any stress which does not exceed the elastic limit can result in changes such as are shown in Fig. 27. This means that there must be sufficient room inside the aluminum can in which the core is housed for its thermal expansion. Also, it might be necessary to support part of the core separately as shown in Fig. 28 if the effects of high "g" and vibration had too great an effect on the hysteresis loop.



MAGNETIC CORE

ALL DIMENSIONS IN INCHES

SCALE: 1" = 1" (AS SHOWN)

DATE: 10-1-68

BY: [Signature]

FOR: [Signature]

PROJECT: [Signature]

DESCRIPTION: [Signature]

REVISIONS: [Signature]

APPROVED: [Signature]

DATE: 10-1-68

BY: [Signature]

FOR: [Signature]

PROJECT: [Signature]

DESCRIPTION: [Signature]

REVISIONS: [Signature]

APPROVED: [Signature]

DATE: 10-1-68

BY: [Signature]

FOR: [Signature]

PROJECT: [Signature]

DESCRIPTION: [Signature]

REVISIONS: [Signature]

APPROVED: [Signature]

DATE: 10-1-68

BY: [Signature]

FOR: [Signature]

PROJECT: [Signature]

DESCRIPTION: [Signature]

REVISIONS: [Signature]

APPROVED: [Signature]

DATE: 10-1-68

BY: [Signature]

FOR: [Signature]

PROJECT: [Signature]

DESCRIPTION: [Signature]

REVISIONS: [Signature]

APPROVED: [Signature]



REMARKS 25% Silicon Iron

$H_m = 10 \frac{A}{cm}$

Stack of 4 cores, each 15mm high

Core assembled with (1) washers-tightened

(2) washers removed

(3) twine bands removed

(4) pre-excitation windings removed

Fig 27

CUSTOMER

PROJECT

PREPARED BY: [Signature]

DATE: 10-1-68

VER

DATE

10-1-68

10-1-68



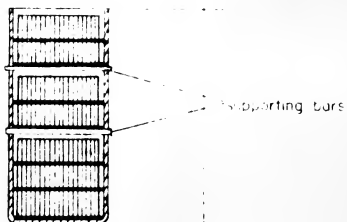


Fig-28

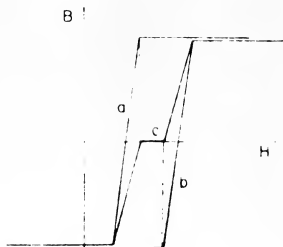
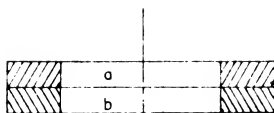


Fig-26







## CHAPTER IV

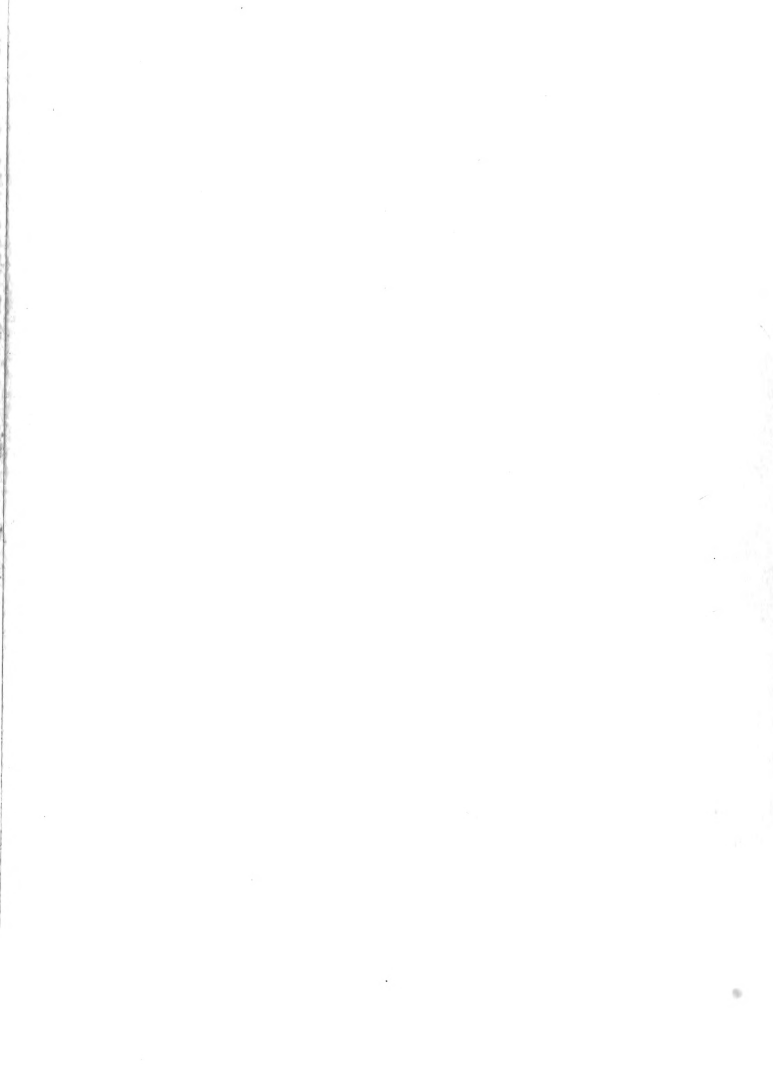
### PRE-EXCITATION

#### 1. General

The requirement of this rectifier that there be a magnetic voltage control system automatically dictated two separate and complete pre-excitation systems. The first, the AC system, is the one described in the Introduction. It is always required to insure positive current flow through the contacts as they open, for the reasons outlined there. In addition to this, a DC pre-excitation is required with magnetic voltage control to control the amount of magnetism of the core when the contact closes. As a result, the DC winding is put on so that it neutralizes the effect of the AC winding during the make step and aids during the break step. This is a disadvantage during the break step, however, since it results in a variation of the current flowing through the contacts at the break as a function of load current. (Voltage control)

The core acts as a conventional transformer during the step and as a result, some impedance must be placed in the line to keep the pre-excitation current at the desired value. This could be a resistor but this would involve large losses. For this reason, an inductance is much more satisfactory.

The inductance in the AC pre-excitation circuit not only limits a transient change in current during the step but also limits the amount of current flowing. This double



requirement makes the AC pre-excitation very inflexible and as a result, it will be considered first.

## 2. AC Pre-excitation.

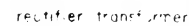
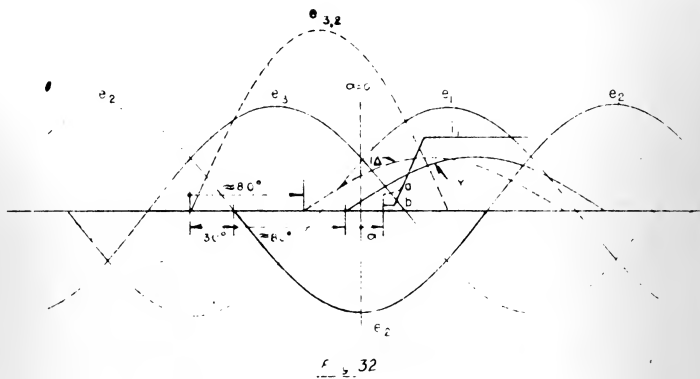
There are two simple connections possible for AC pre-excitation, Y, Fig. 29 or  $\Delta$ , Fig. 30. The phase relations for the two connections are shown in Fig. 31 for the break step and Fig. 32 for the make step. As can be seen, the optimum is between the two connections. For this design, - the  $\Delta$  connection seemed better since it supplied more ampere turns prior to the time the contacts closed. This in turn results in a higher flux density and less saturation delay at rated load and above. It does have the disadvantage, however, that during the break step, the pre-excitation begins to decrease when it should be still increasing. The increase would be an advantage, since the step is shorter at the higher loads. This is true because the effective value of the commutating voltage is larger. This results in a larger hysteresis loop and so more ampere turns.

The double requirement for the inductance, in effect, dictates how many turns of pre-excitation can be used on the core. The equation can be derived to solve this problem as follows:

Let  $z$  be the per unit change in pre-excitation current.

$$z = \frac{i_p}{I_p} \quad (\text{Fig. 33})$$





stabilizing reactor

pre-excitation  
windings

*Fig 29*

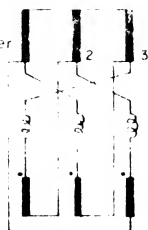
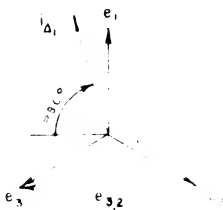
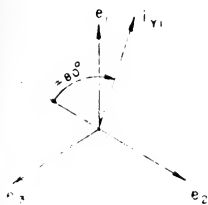
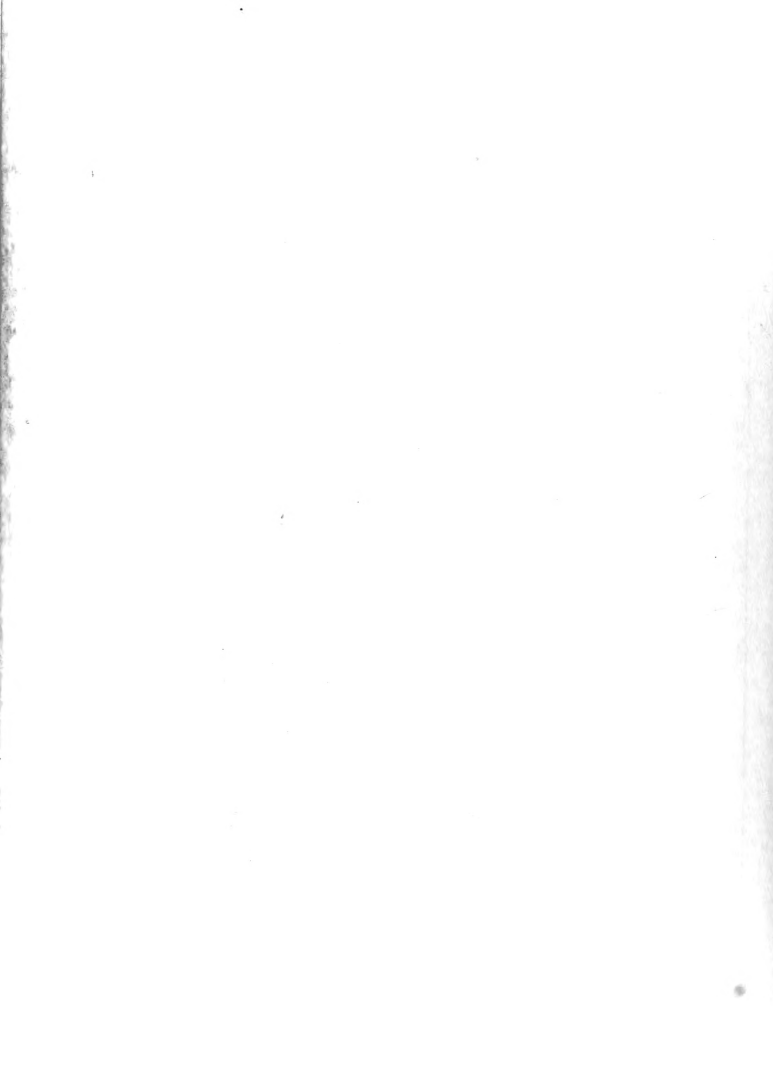


Fig 30





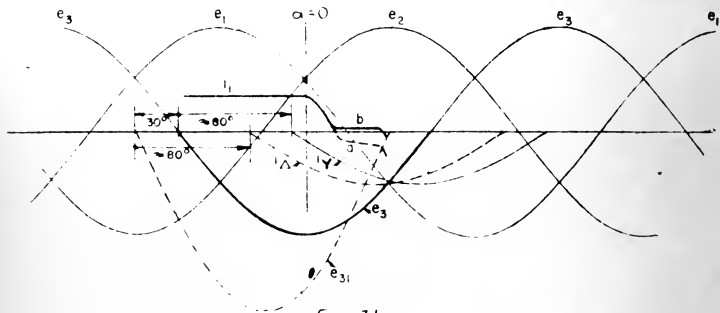


Fig 31

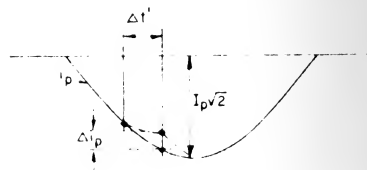
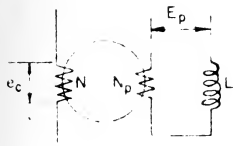
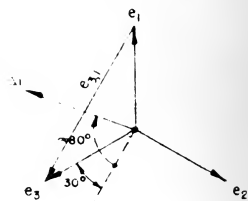
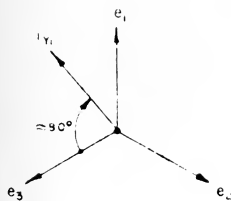


Fig 33





Neglecting the small amount of inductance in the turns on the coil and calling the limiting inductance  $L$ .

$$I_p \approx \frac{E_p}{L\omega}$$

Also

$$e = L \frac{di}{dt} \quad \text{or} \quad \Delta i = \frac{L}{L} \int_0^{\Delta T} e \cdot dt$$

Considering now the transformer action during the step. If  $N_p$  is the maximum number of turns in the AC pre-excitation winding on the core:

$$e = \frac{N_p}{N} e_c = \frac{N_p}{N} E_c \sqrt{2} \sin \omega t$$

Therefore

$$\Delta i = \frac{E_c \sqrt{2}}{L} \frac{N_p}{N} \int_0^{\Delta T} \sin \omega t = \frac{E_c \sqrt{2}}{L \omega N} \frac{N_p}{N} \{1 - \cos \omega \Delta T\}$$

Therefore

$$z = \frac{\frac{E_c \sqrt{2} N_p}{L \omega N} \{1 - \cos \omega \Delta T\}}{\frac{E_p}{L \omega}} = \frac{E_c \sqrt{2} N_p}{E_p N} \{1 - \cos \omega \Delta T\}$$

$$\text{or } N_p = \frac{z N E_p}{E_c \sqrt{2} \{1 - \cos \omega \Delta T\}}$$

For this rectifier, with a  $\Delta$  connection, an assumed value of  $z$  of .2, and a calculated minimum possible step length of 45.4°.

$$N_p = \frac{.2 \times 70 \times 208}{244 \{1 - \cos 45.4^\circ\}} = 35.3$$

Use 33 turns



The value of H required at the end of the break step for a  $\beta$  of 13 kilogauss was estimated from Figs. 17 and 18 to be .7 oersteds at 400 cycles. During the make step, there should be about .5 oersteds at the moment the contacts close to bring the flux density up to 13 kilogauss. (Fig. A-46 Appendix I.)

Assuming that the maximum value of pre-excitation occurs when a maximum value of pre-excitation is required:

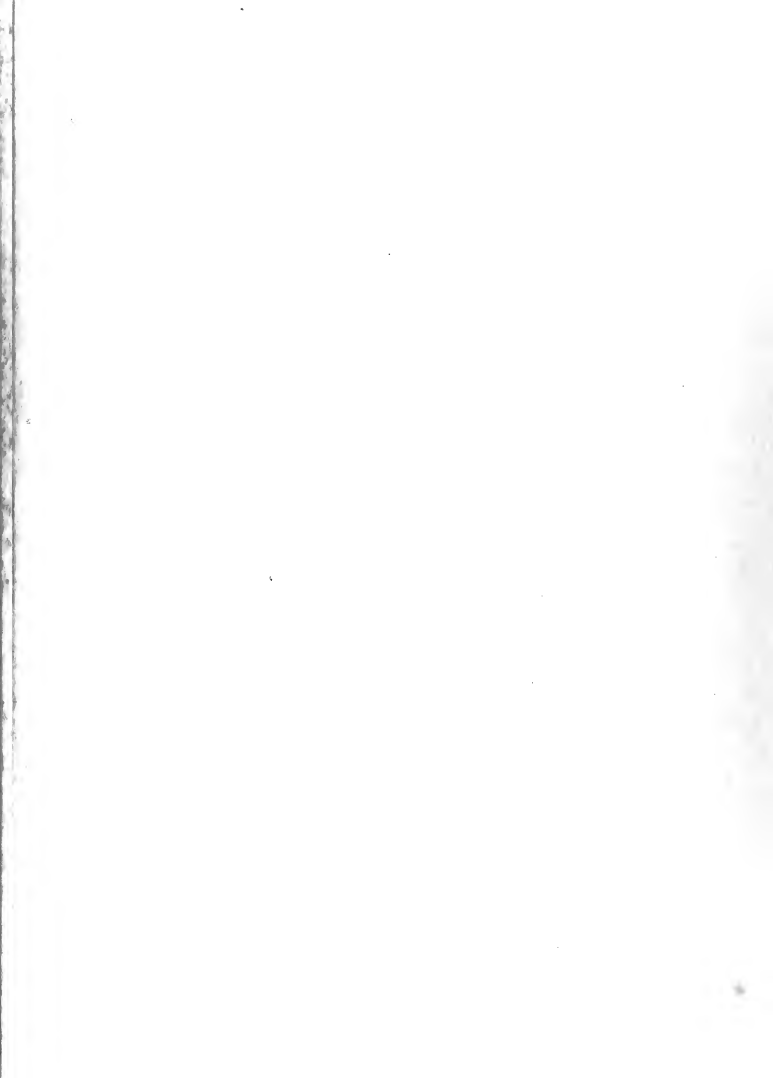
$$I_p = \frac{H_z \times L_m}{(1-z) \sqrt{2} N_p} = \frac{1.7 \times 19.6}{(1-.2) \sqrt{2} \times 33} = .735 \text{ amps.}$$

The value of L which will not only limit the value of z to .2 but also limit the total current to .735 amps will be:

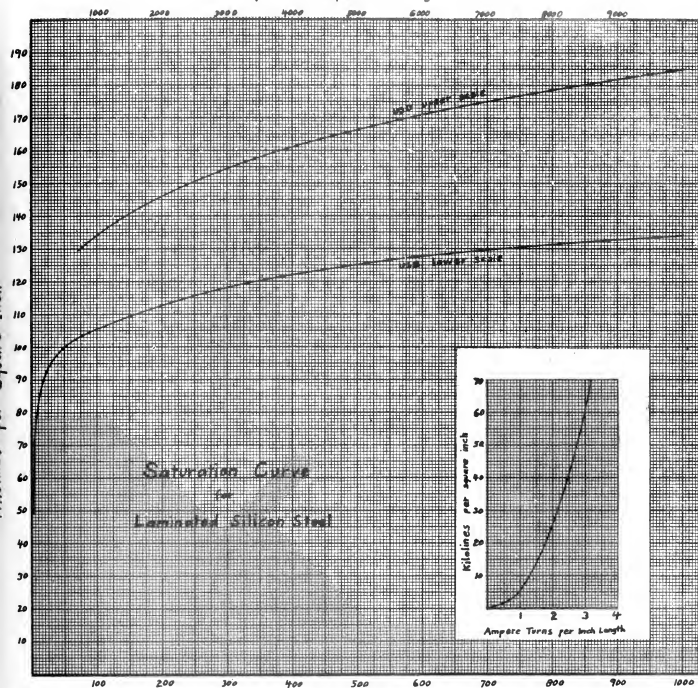
$$L \cong \frac{E_p}{I_p \omega} = \frac{208}{.735 \times 800 \pi} = .1128 \text{ henries}$$

The design of the pre-excitation circuits is at best approximate. Therefore, Dr. Rolf (3) recommended that the choke be made variable  $\pm 25\%$ . He suggested a change in the width of an airgap but multiple taps would seem to be better for this design. A total of eleven taps from - 25% to + 25% of the design value should be more than adequate.

The design of the choke was conventional using a toroidal core, silicon steel with a magnetic saturation curve shown in Fig. 34 which gave a core permeability of 4,000 at 50AT/inch. The copper winding, #22 wire (870 circular mils / ampere) with characteristics again from Circular #31 of the US Bureau of Standards, R of 19.0 ohms/



Ampere Turns per Inch Length



Saturation Curve  
for  
Laminated Silicon Steel

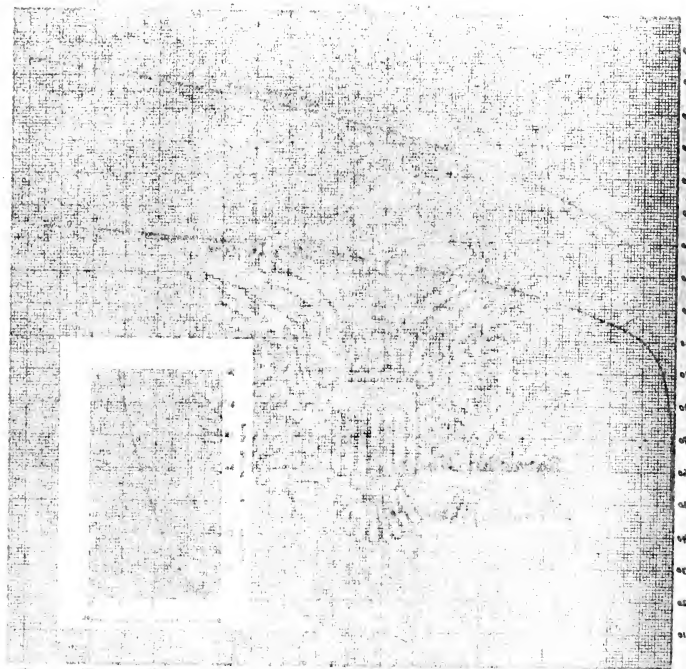
Ampere Turns per Inch Length

RP 271

11 Sept. 1940

at

Fig 34



1000 feet at 35°C and 1.94 pounds/1000 feet.

$$L = .1128 \times 1.25 = .141 \text{ h}$$

$$\text{Core area} = .8 \text{ sq. cms.}$$

$$d_m = 2.9 \text{ cms.}$$

$$N = 179 \text{ or } 36 \text{ AT/in.}$$

$$\text{Copper length on choke} = 179 \times \frac{1.8 \times 4}{2.54} = 252 \text{ in.}$$

$$\text{Copper length on main core} = \frac{18.16 \times 33}{2.54} = 236 \text{ inches}$$

Allowing 30 inches for internal connections

$$\text{Total copper length} = 252 + 236 + 30 = 518 \text{ inches}$$

$$I^2R/\text{core} = \frac{518}{1000 \times 12} \times 19(.735)^2 = .444 \text{ watts}$$

$$\text{Therefore: Total loss } 3 \times .444 = 1.332 \text{ watts}$$

$$\begin{aligned} \text{Copper weight} &= .8 \times 29 \pi \times 7.87 \times 3 \times 2.20 \times 10^{-3} \\ &= .3795 \text{ lbs.} \end{aligned}$$

Allowing .2 lbs for potting

$$\begin{aligned} \text{Total AC pre-excitation weight} &= .25 + .3795 + .2 \\ &= .83 \text{ lbs.} \end{aligned}$$

### 3. DC Pre-excitation

The DC pre-excitation has only one purpose - to limit the AC pre-excitation at loads below rated so that the output voltage will be maintained at the value dictated by the voltage regulator. This requires that the current be varied





from a minimum of zero at rated load and above, to a maximum at base load.

The design data from Chapter III showed that a maximum delay voltage area at base load was .021 volt secs. The saturation delay will account for .00686 volt seconds which leaves .01444 volt seconds to be taken care of by magnetic delay. However, the total area available is .0900 volt seconds. This means that the value of  $\Delta B$  which must be available is:

$$\Delta B = \frac{\text{voltage area}}{NA_{Fe}} = \frac{.0144}{346 \times 10^{-4}} = .417 \text{ webers or } 4.17 \text{ kilogauss}$$

This means that the AC pre-excitation must be reduced so that the flux will be no greater than 10 - 4.17 or 9.83 kilogauss. This corresponds to a .2 oersteds, referring to the DC hysteresis loop, Fig. 19, to be conservative. This means that the DC pre-excitation must be able to furnish 1.4 - .4 or 1 AT/inch or a total of 1 x .9.6 or 19.6 AT.

This number of ampere turns could be supplied in almost any combination. The design of the voltage regulator would undoubtedly be the determining factor. If we assume the maximum heat dissipation to be the determining factor, and assume this maximum to be 75 watts. The limiting current would be .65 amperes at base load if we assume negligible resistance in the rest of the circuit.

The number of turns for the DC pre-excitation on each main core would then be  $\frac{19.6}{.65} = 30.2$  turns. If 30 turns is used, the next problem is a choke similar to the one designed



for the AC pre-excitation. This inductance does not have a double purpose however so that the design is not particularly critical.

If a  $z$  of .2 is again assumed, the  $\Delta I_{pdc}$  will be .2 x .65 or .13 amperes. Using the same design formulae as before:

$$L_{dc} = \frac{E_c \sqrt{2} N_{pdc}}{\Delta i_p \omega N} \left\{ 1 - \cos \omega \Delta T \right\}$$

$$= \frac{294 \times 30}{.13 \times 800 \pi \times 70} \left\{ 1 - \cos 45.4 \right\} = .1145 \text{ henries}$$

There appears to be no reason to increase this as was done for the AC pre-excitation since it is not critical. Using #22 wire or 1000 circular mils/ampere and as before:

19.0 ohms/1000 feet at 65°C.

1.94 lbs/1000 feet

Permeability of 160 at 100 AT/inch

Core area = 2.0 sq. cms.

$d_m$  = 3.4 cms.

$N$  = 570 turns or 88 AT/inch

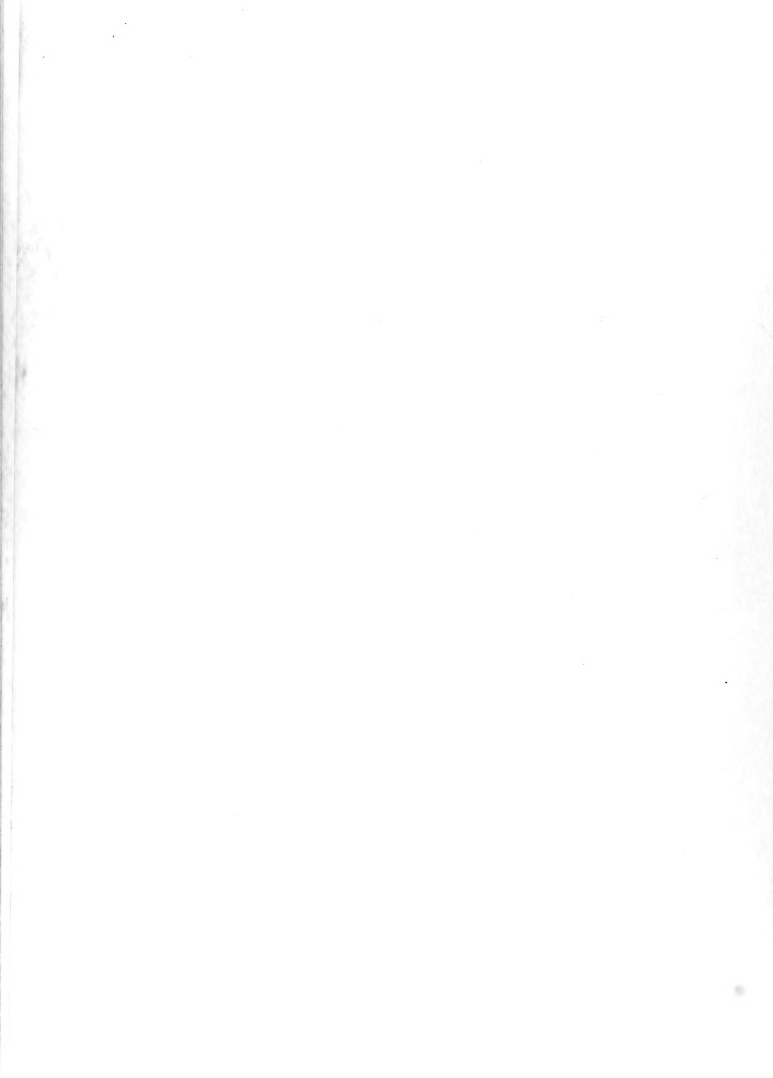
Copper length =  $\frac{570 \times 2 \times 4}{2.54} = 1270$  inches

Copper length on each main core =  $\frac{12.16 \times 30}{2.54} = 215$  in.

Allowing 60 inches for internal connections

Total copper length  $1270 + 215 \times 3 + 60 = 1975$  inches

Total copper weight  $\frac{1975 \times 1.94}{1000 \times 12} = .319$  lbs.



Core weight  $2 \times 10.7 \times 7.87 \times 2.205 \times 10^{-3} = .375$  lbs.

Allowing .2 lbs. for potting.

Total DC pre-excitation weight less regulator =

$$.319 + .375 = .694 \text{ lbs.}$$

The regulator required for this type rectifier can be any of the common types. A carbon pile would have to work opposite from the ones designed to operate in the field circuit of a generator. The minimum resistance of  $\frac{115 \text{ volts}}{.55 \text{ amps}}$  or 177 ohms could either be a limiting resistor or be the lowest resistance of the regulator; varying from there to infinity.

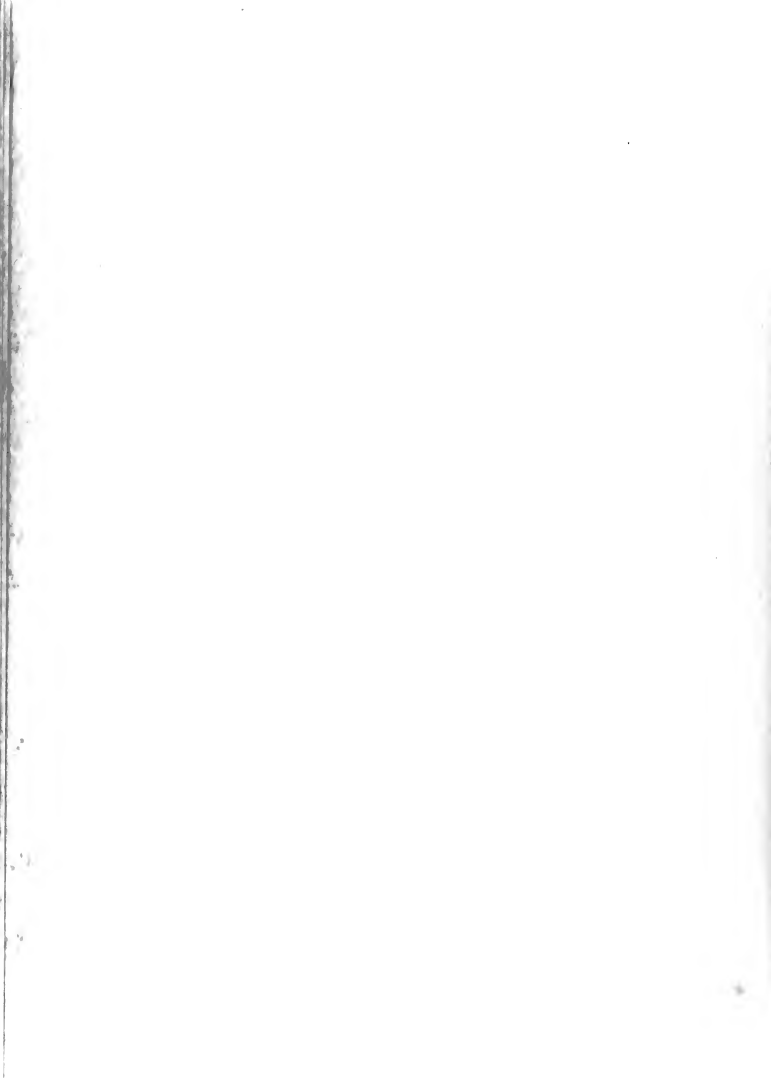
The voltage control will be as accurate as the regulator used, until rated load is reached.

#### 4. Base Load.

The DC pre-excitation would appear to be a perfect source of base load, and it is, except for military installations. For these, an interruption of the load at rated load or above would result in no base load until the regulator could react. For this reason, some provision must be made for a base load which will always be connected.

Any dependable load can be used but to make this design complete, a minimum base load was designed. The base load must be large enough to at least produce a flux density of 13 kilogauss. This will require a minimum of .4 oersteds. In addition to this, it must neutralize the AC pre-excitation of .7 oersteds. This means that the base load current must produce at least 1.1 oersteds, or:

$$\frac{43AT}{70} = .615 \text{ amperes.}$$



This is the minimum value of the base load current. The DC output voltage of course has ripple and this must be considered, either by using a choke in the base load circuit or by drawing excessive current.

The critical time exists for no external load and no DC pre-excitation, for this condition, the DC voltage would jump to approximately 135 volts since there would be no appreciable delay. This can be determined by knowing that the combination of AC pre-excitation and the base load current will produce an mmf of  $1.1 + .7$  or  $1.8$  oersteds. This gives a  $\beta$  of about 14.2 kilogauss or a delay of  $.12 \times 10^{-4} \times 346 = .00416$  volt seconds. This will mean a voltage of  $(.117 - .00416) \times 1200 = 135$  volts.

Referring again to Dr. Rolf (3), the necessary smoothing inductance is:

$$L = \frac{E_o}{\omega} \cdot \frac{\delta}{\Delta I_d}$$

For a voltage area delay of .00416, this will amount to 150 and so  $\int$  from Dr. Rolf (3) is .21. Limiting  $\Delta I_d$  by assumption to .2 amps,

$$L = \frac{135}{800} \times \frac{.21}{.2} = .0565 \text{ henries}$$

Using the same core as was used in the AC choke and the permeability of the DC choke:

$$N = 565 \text{ or } 128 \text{ AT/inch}$$

With #21 wire,  $R = 15.1$  ohms/1000 feet, weight 2.45 lbs/1000 ft.

$$\text{Copper length} = \frac{565 \times .8 \times 4}{2.54} = 798 \text{ inches}$$

\*This is not the same  $\delta$  used by Koppelman in his work; Koppelman (2)





Allowing 15 inches for connections

Copper length =  $798 + 15 = 813$

Copper weight =  $813 \times 2.45 = .166$  lbs.

Core weight = .1265

Allowing .15 lbs for potting

Base load resistor  $\frac{115}{.615 \pm 2} = 141$  ohms

Therefore EI =  $115 \times .815 = 93.7$  watts

Resistor weight = .119 pounds

Therefore, total base load circuit weight is:

$.166 + .2765 + .119 = .5615$  lbs.



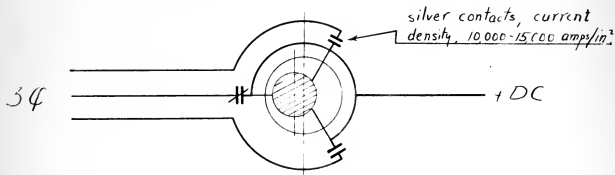
CHAPTER V  
THE CONTACT MECHANISM

1. Requirements and Limitations

The design of the Contact Mechanism is essentially a mechanical problem. For this reason, only a brief study was made of this unit. This does not mean that there will not be some problems in making the unit work properly at 400 cycles. However, the main requirements for any contact unit, no matter what the frequency may be are:

- (1) The contacts open and close at the correct time.
- (2) They open faster than the voltage builds up.
- (3) They seat firmly and do not bounce.

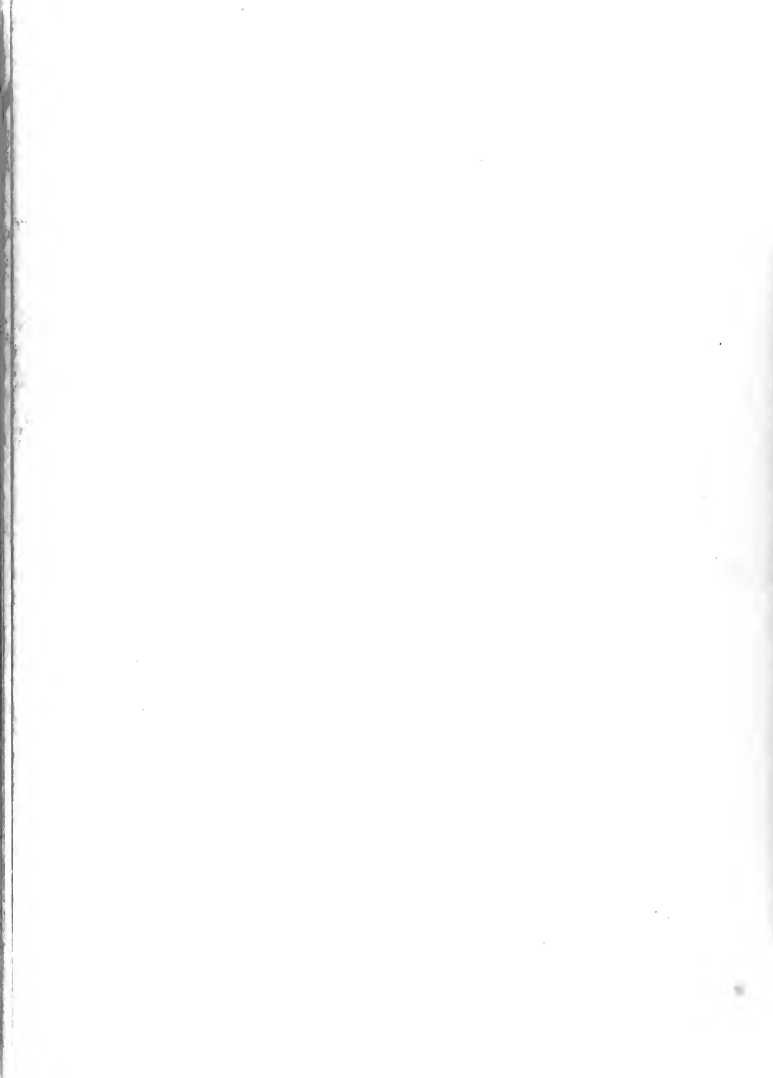
Two general systems are used for mounting the contacts, in line and radial. The radial scheme would appear to be the lightest and simplest for this power rating. The general layout is illustrated in Fig. 35 and the push rod and contact movement in Fig. 36.



Radial Installation of Contacts

Fig. 35

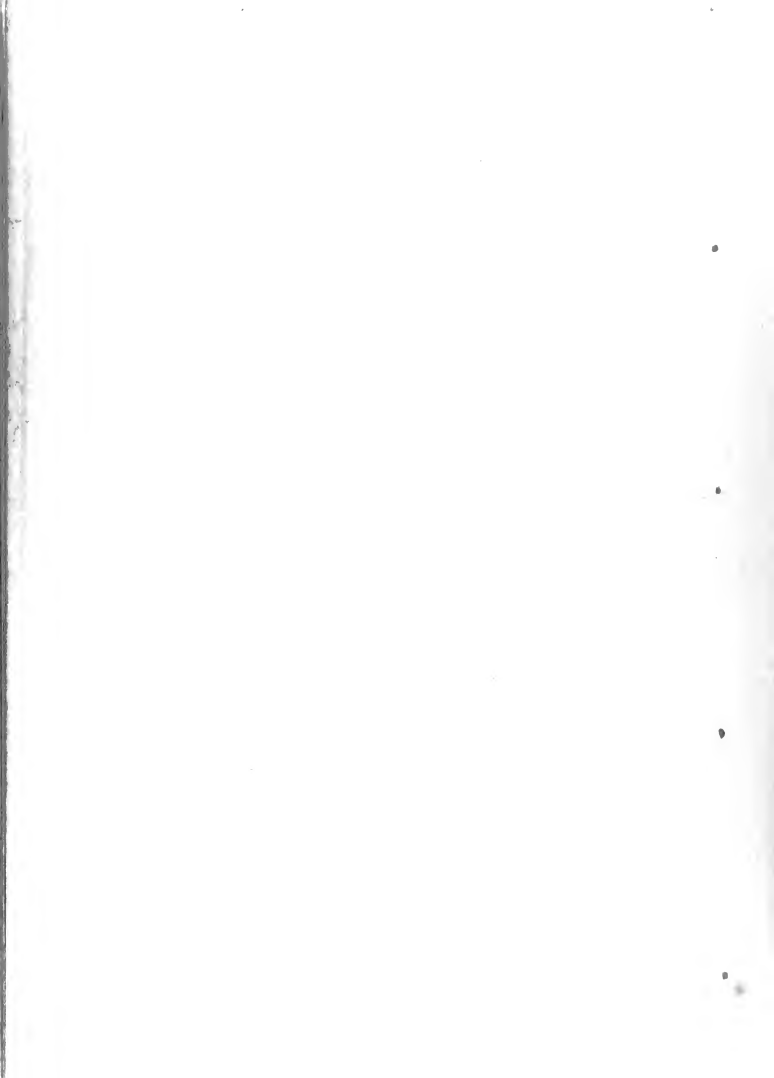
The contact mechanism at conventional frequencies has posed no problem which could not be solved by good design.



The design has also been complicated by requirements for shift in contact timing, adjustment while the unit is running, and obtaining a prime mover which was stable. In this design, it was planned to have the contact mechanism driven by the same gear train which drives the alternator. This solves one of the most troublesome problems found in conventional installations, i.e. finding a small synchronous motor which is very stable and has the same angle of lag under all operating conditions. The contacts should open and close at the desired time dependably regardless of what the operating conditions may be, if the unit is geared directly to the alternator. However, the driving cam must run at a high speed. The normal method using a conventional eccentric requires a speed of 24,000 RPM at 400 cycles. The eccentric would probably have a sleeve bearing riding on it upon which would rest the contact push rods.

## 2. Installation and Adjustment

There must also be a provision for rotating the entire mechanism during the initial adjustment of contact timing. There are two variables involved in timing the contacts, orientation of the eccentric and overlap time. Orientation of the eccentric will affect the closing and opening time and can be changed by revolving the entire mechanism. Overlap time can be changed by changing the contact travel, Fig. 30, and so the total closed time. Juggling of these two using an oscilloscope with the voltage across the contacts on the vertical plates to show whether the contact voltage is



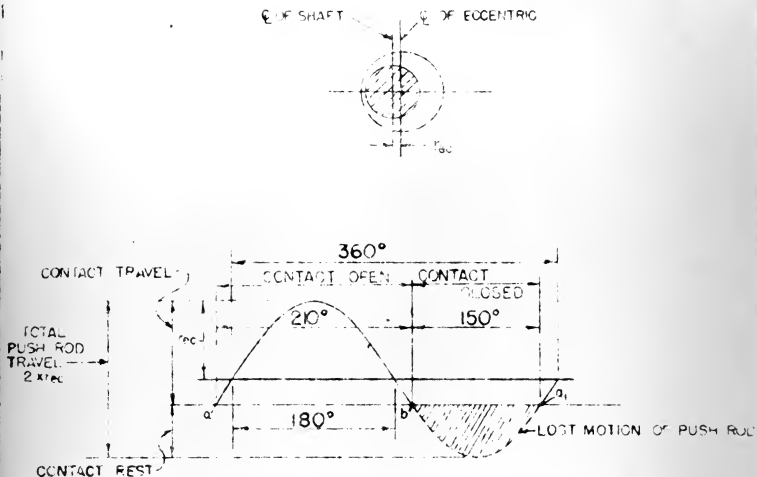


FIG 36  
PUSH ROD AND CONTACT MOVEMENT

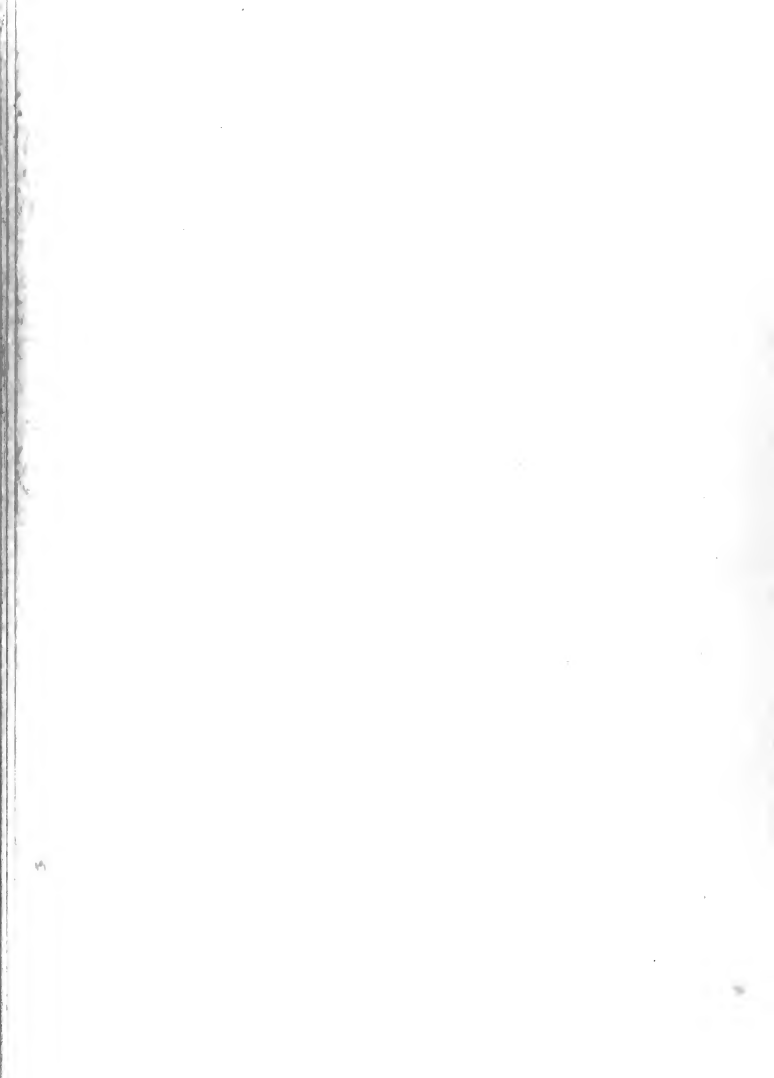




zero at closing, Fig. 2, will be required. Also, some provision for showing when, in time, the contacts should open, will be required. This can be considerably simplified, however, if the contact travel is preset during manufacture, then only the orientation need be adjusted. This is a very simple procedure using an oscilloscope. The only problem would be checking phase and phase rotation. This is common to all 3 phase power.

This may seem to be a complicated process but it need only be done at initial installation, later if the power source is changed, and for preventive maintenance, perhaps, if tests show this to be necessary.

It has been found at the conventional power frequencies that if the spring force on the individual reciprocating parts of the contact was 1000 times the weight of the part, there would be no bouncing. The speed of opening and closing need be no faster at 400 cycles than it is at 60 cycles to satisfy Koppelman's (2) requirement of an opening speed of 1 meter/second. If this is true, the accelerating forces encountered will be the same as at 60 cycles. The required eccentricity, however, for this limitation is only .4mm. While the voltages involved are low enough so that theoretically, with a pressurized space, no arc is possible, it is probable that this distance would have to be made greater to give dependable operation. During operation, there is some pitting and this tends to reduce the actual spacing to a lesser value than the contact movement would indicate. ITE uses .1 inches as a standard opening but this is dictated by



opening speed.

Dr. Rolf (3) states that there is some glow discharge if the voltage across the making contacts is more than 275 volts, for silver. In this unit, there should be zero voltage across the contacts at make. Therefore, the only criteria should be that they separate far enough so that this phenomena will not occur when the inverse voltage reaches the peak value of about 400 volts. This rectifier has so many turns on the main winding and the pre-excitation has been so designed that excessive currents at make and break should not be encountered. Fig. 37.

Fig. 38 shows the design used by the Germans in their small rectifiers, it would appear that a similar design would be the best system for this rectifier too. It could be easily replaced by a crewman in event of a flash over. This could be done by taking out the bolt shown and replacing the entire unit. Proper quality control would make the contacts interchangeable with no readjustment of the unit. This change then would require repressurizing in flight but nothing more.

### 3. The RC Parallel Circuit.

The current flowing through the contacts as they start to open has been made very small. However, to prevent contact damage by a sudden voltage build up as a result of the inductance in the circuit, the contacts are always shunted with a conventional RC circuit if the type of pre-excitation provided for in this design is used. The circuit



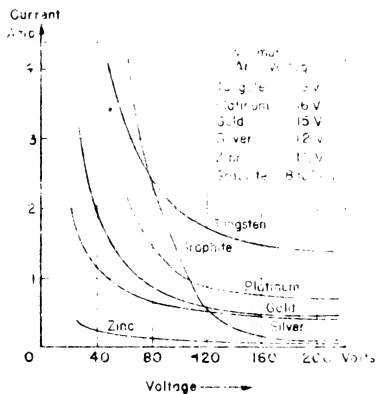
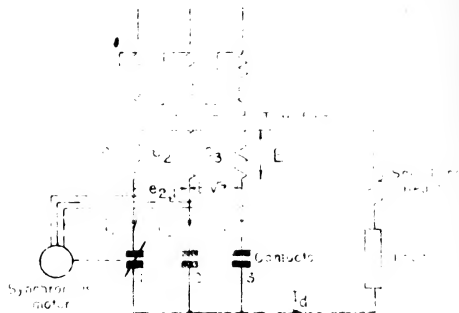


Fig. 37





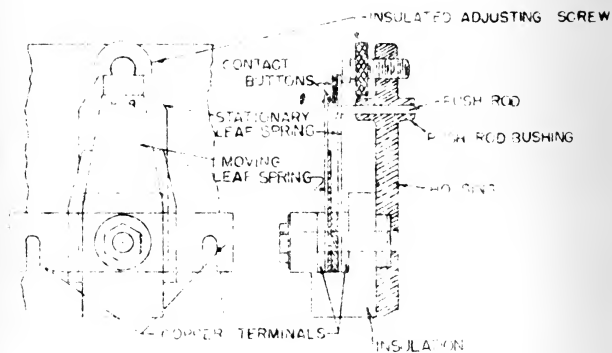


FIG 38  
LEAF SPRING CONTACT





is shown in Fig. 39. The current directions are at the instant the contacts close.

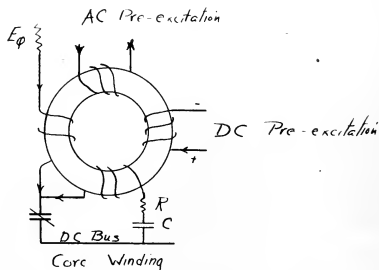


Fig. 39

The value of  $R$  is a function of the current flowing through the contacts at the instant of opening. Dr. Rolf (3) states that the amplitude of  $\Delta i \times R$  should be 10 to 15 volts.

The value of  $\Delta i$  will be largest for the base load because at that time, the maximum DC pre-excitation will be aiding the AC pre-excitation. This is then the critical condition and the one which should be designed for. The actual value can be only approximated since it is only as accurate as the estimate of the probable pre-excitation. This again is a function of the size of the hysteresis loop, which changes drastically within the range of step time through which this unit will operate, .3 to .6 milliseconds. Figs. 15, 16, 17 and 18.

The maximum probable value was determined by taking the maximum AC and DC pre-excitation and subtracting the probable minimum number of ampere turns required for remag-



netization. This gives the following results:

$$\begin{array}{rcl} \text{AC} & .735 \times 33 \times \sqrt{2} & 34.3 \text{ AT} \\ \text{DC} & & \frac{19.6 \text{ AT}}{53.9 \text{ AT}} \end{array}$$

Figs. 15 and 16 show that the minimum field strength when the contacts open at base load will be .4 oersteds for a  $\beta$  of 7 kilogauss. This means that 17.7 AT will be required for actual magnetization leaving a maximum of 36.2 to produce positive current in the main winding. As a result, a maximum of  $\frac{36.2}{70}$  or .512 amps will be flowing through the contacts at the time that they open. Referring again to Fig. 37, for silver contacts, there will undoubtedly be no arcing since the voltage will be low but it would be preferable if the current could be reduced more. It may be found if this design is built that the pre-excitation can be successfully reduced, this would then reduce the current when the contacts open. In practice, it has been found necessary to adjust the pre-excitation after the unit was operating.

The RC circuit is still used, even though the current is low, to reduce contact wear when this type of pre-excitation is used.

From Koppelman (2)

$$\frac{de}{dt} = 10^5 = \frac{e}{C}$$

$$\text{or } C = \frac{.512}{10^5} = 5.12 \mu f \quad \text{Use } 5 \mu f.$$



The value of R from Dr. Rolf (3) should be:

$$R = \frac{L}{\Delta i} = \frac{15}{.512} = 29.2 \Omega$$

$$U_{st} = 30 \text{ ohms.}$$

The biggest question in this particular part of the design was the wattage of this resistor. The voltage wave across the contacts is so complex, and there are so many unknowns that an exact solution does not appear practical. As an effort to obtain any kind of an answer, the wave form for the rectifier shown in Fig. 40 was used to estimate the maximum probable voltage across the contacts. From this, it was assumed that the maximum voltage across the contacts would be 400 volts. If we assume, for lack of something better, that this voltage wave can be represented by a sine wave of maximum amplitude 400 volts peak to peak and a frequency of 400 cycles, the following analysis will apply:

$$X_c = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 400 \times 5 \times 10^{-6}} = 79.6 \Omega$$

$$I = \frac{E}{Z} = \frac{200}{\sqrt{2} (30 - j 79.6)} = 1.668 \text{ amps.}$$

$$I^2 R / \phi = (1.668)^2 \times 30 = 83.4 \text{ watts}$$

$$\text{Total RC loss} = 3 \times 83.4 = 250.2 \text{ watts}$$



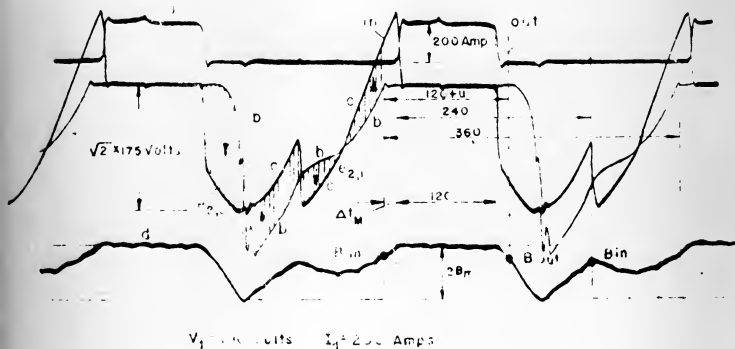


Fig 40





As can be seen, this is one of the major losses and it was unfortunate that it had to be based on so many approximations.

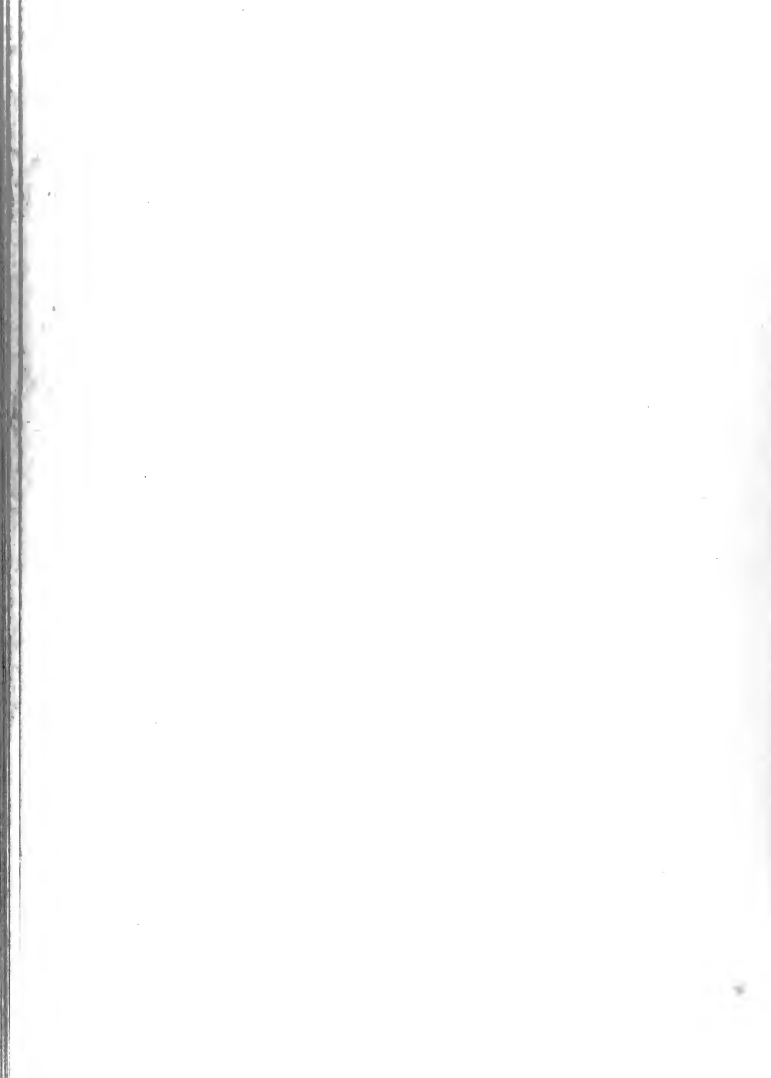
The weight of the 3 resistors and the 3 condensers in one can should be about 2 pounds.

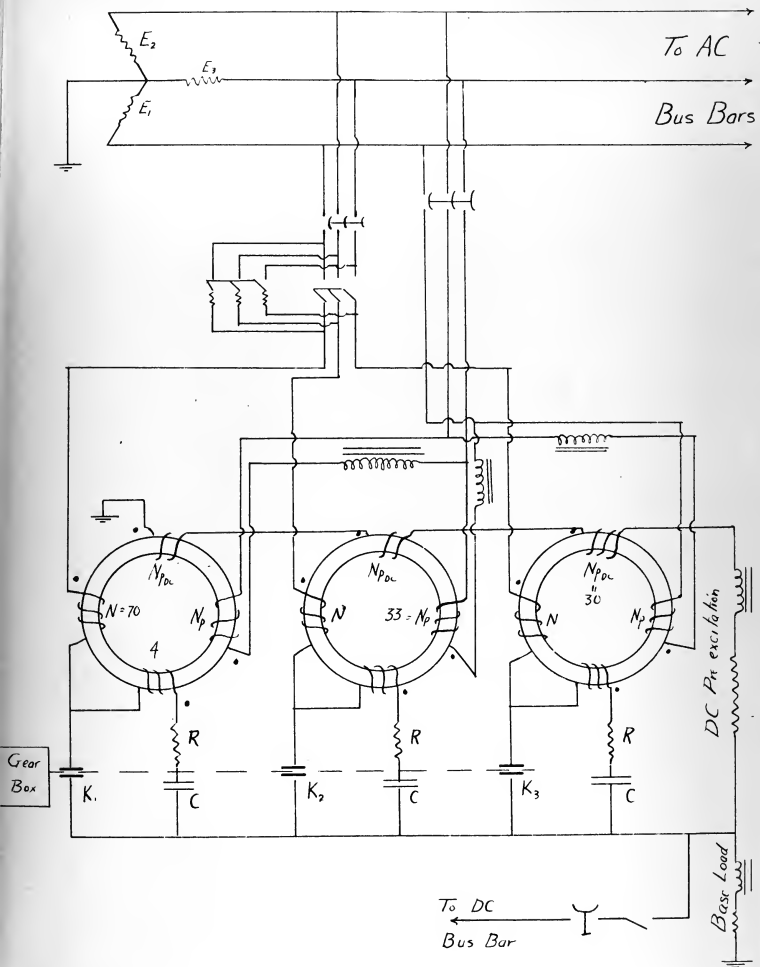
The weight of the contact mechanism is also a guess. If an estimate is made based on a 50 ampere 60 cycle unit built by ITE, it will be a cylinder 3 inches in diameter and 4 inches long. If the weight is estimated on the basis of a piece of solid steel, 2 inches in diameter and 3 inches long, this will have a weight of 2.68 lbs. The cover for pressurizing the contacts should weigh no more than .2 pounds.

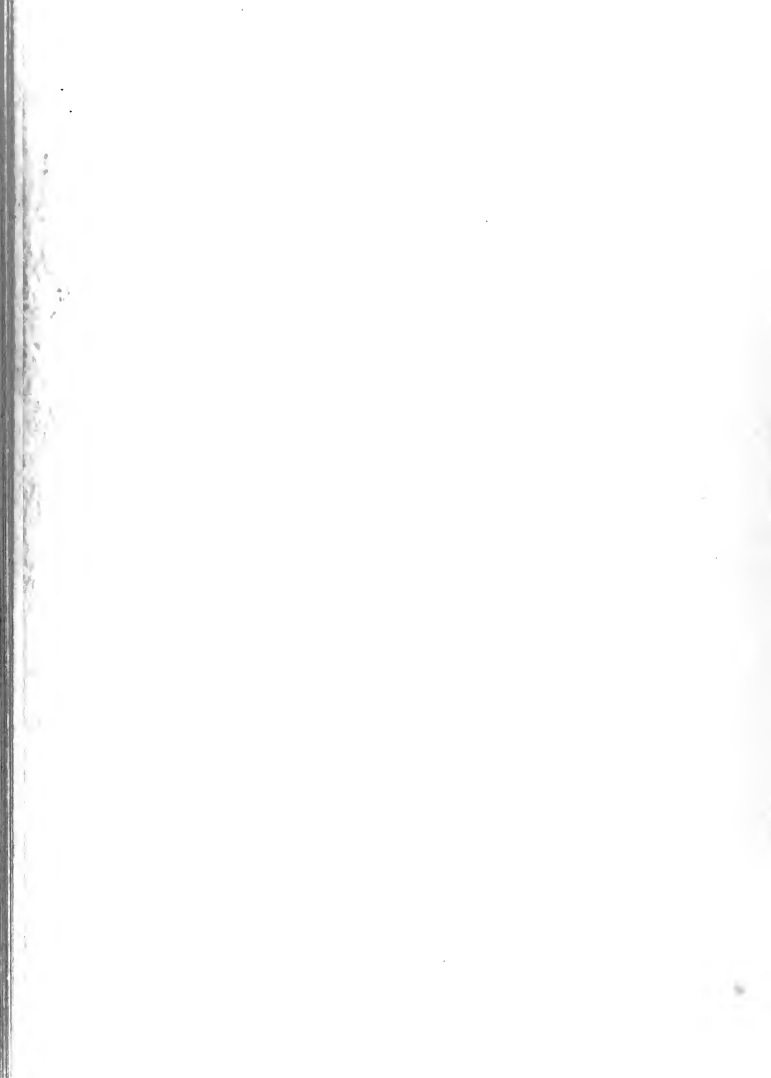
The total contact mechanism should then weigh no more than:

$$.2 + 2.68 + 2 = 4.88 \text{ lbs.}$$

The turns on the core of the RC circuit will supply at least the .1 Kilogauss which was not included in the saturation delay, perhaps more. This represents an area of .000346 volt secs. These turns not only aid in this way but they also prevent a large surge of current from flowing as the contacts close. From Eq (5), the number of turns should be:  $\frac{.000346}{4.95 \times (1.50-1.30) \times 10^{-4}} = 3.3$ . Use 4 turns.







## CHAPTER VI

### CIRCUIT PROTECTION

It would seem from first impression that this type of rectifier would be extremely sensitive to fluctuations in frequency and voltage. However, it was shown in Chapt. III that this was not the case, as a result of the large design overload capacity.

This reduces the overload protection on the AC side to the usual thermal overload circuit breakers. There should be two sets, however, as shown in Fig. 41. One ampere breakers for the AC pre-excitation circuit and 100 ampere breakers for the main connections should be adequate.

The circuit protection on the DC side is much more complex however. This is the breaker which will largely determine whether the overload will reach too high a value. This should normally not be a severe limitation since the rectifier is largely self limiting as was shown in Fig. 25. The output voltage at the higher loads is so low that only a major fault could ever have a low enough resistance to draw that much current.

A more severe limitation is the subject of reverse current. As was explained in Chapt. III, there must always be a base load. In fact, a base load resistor was put in just to supply that requirement. This means that either there must never be any reverse current, by proper adjustment of the voltage regulator, or an additional base



load must be added which will draw as much current as is required to make it react. Also, the DC breaker must always open before the AC breaker or else the unit will try to act as an inverter until the first flash over.

It would appear, that it would be much lighter and more economical to insure that a voltage regulator was used which had sufficient regulation to insure that the output of the regulator at base load was always slightly greater than any other voltage source on the bus.





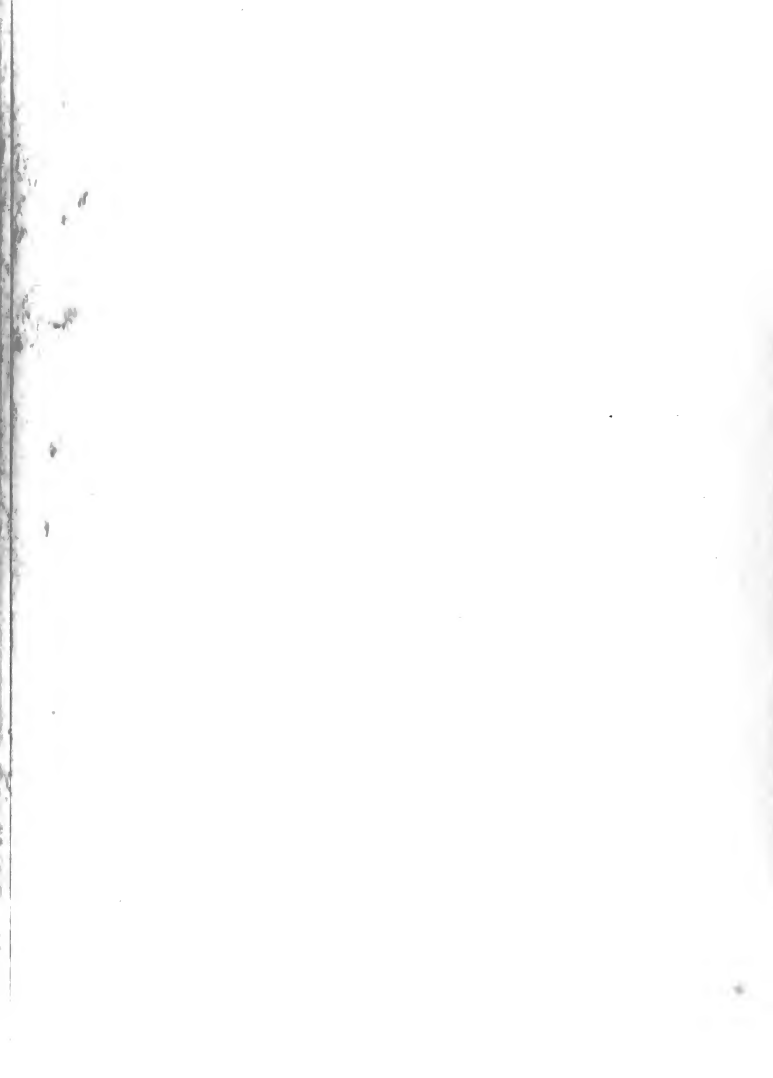
## CHAPTER VII

## PERFORMANCE

## 1. Weight Estimate

The weight of each individual component was estimated as it was designed to give as accurate a composite weight as possible. The following is the weight breakdown:

Cores		lbs.
Iron	3 @ 4.5 lbs.	13.5
Core housing, insulation, mounting, Est.		1.0
Main winding	3 @ 1.5 lbs.	<u>4.5</u>
		19.0
Contacts		
Contact mechanism	Est.	5.0
RC circuit		<u>2.0</u>
		7.0
Pre-excitation		
AC - copper		.25
Choke		.5
		.8
DC - copper and choke		.9
Regulator	Est.	2.5
Base Load Circuit		.6
		<u>4.0</u>
Total weight		30.8
Weight per kilowatt	3.2 pounds.	



## 2. Volume estimate.

The cores are the largest component of any mechanical rectifier, they are usually stacked one above the other.

The following is a volume estimate:

Cores - Housing 7.9 inches wide x 7.1 inches high

Contact mechanism. Est. - 5 inches long x 4 inches Dia.

Therefore the entire rectifier could be put in an enclosure 9 inches high, 9 inches wide and 15 inches long.

## 3. Efficiency.

Fixed losses	Watts
Base load resistor	93.7
Core loss 3 @ 36	108.0
Contact Mechanism driving power neglected	0.0
AC pre-excitation	1.3
AC and DC choke iron loss - neglected	0.0
RC circuit 3 @ 83.4 watts	<u>250.2</u>
Total	453.2
Base Load	
Fixed losses	453.2
DC Pre-excitation	<u>75.0</u>
Total	528.2
Efficiency	0%
$\frac{1}{4}$ Load	
Fixed losses	453.2
DC Pre-excitation	44.0
Main Winding 3 @ $\frac{125}{16}$	<u>23.4</u>
Total	520.6
Efficiency	$\frac{2500}{2500 + 520.6} = 82.7\%$



Watts

 $\frac{1}{2}$  Load

Fixed Losses			453.2
DC Pre-excitation			36.0
Main winding	3	@ $\frac{125}{4}$	<u>83.8</u>
Total			573.0
Efficiency	$\frac{5000}{5573}$	=	89.6%

 $\frac{3}{4}$  Load

Fixed Losses			453.2
DC Pre-excitation			22.6
Main Winding	3	@ $125 \times \frac{9}{16}$	<u>211.0</u>
Total			686.8
Efficiency	$\frac{7500}{8.86}$	=	91.7%

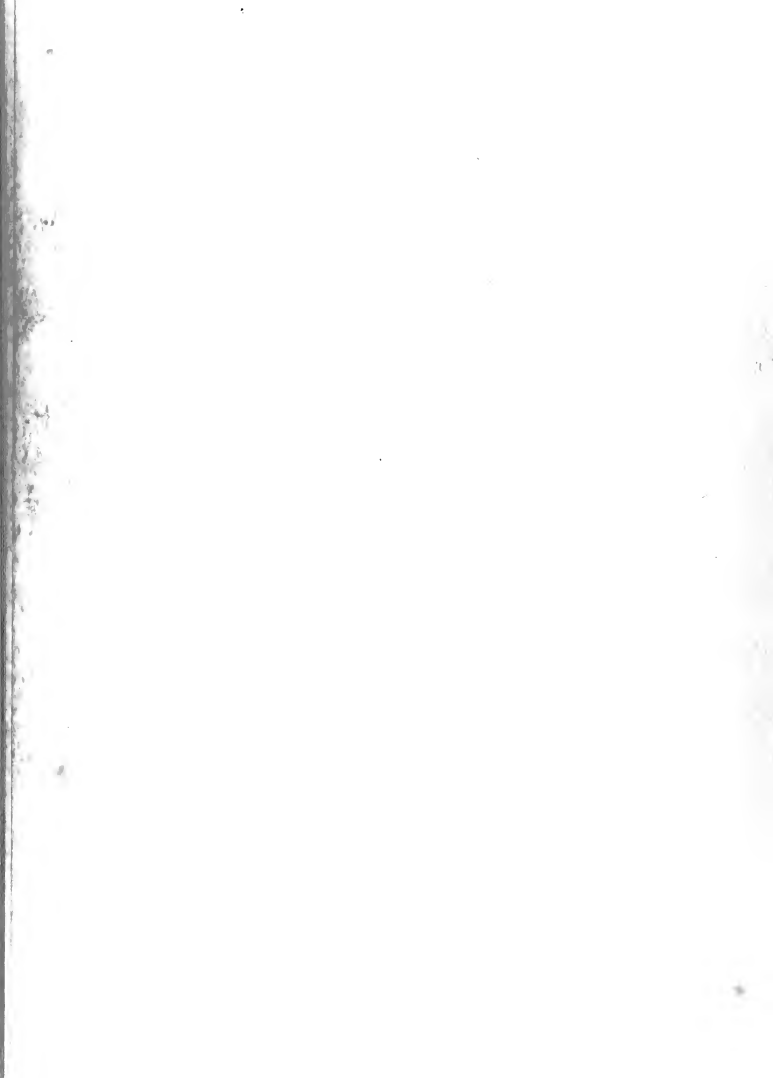
## Rated Load

Fixed losses			453.2
Main winding	3	@ 125	<u>375.0</u>
Total			828.2
Efficiency	$\frac{10,000}{10,828}$	=	92.4%

## 125% Rated

Fixed Losses			453.2
Main Winding	3	@ $125 \times \frac{25}{16}$	<u>586.0</u>
Total			1039.2
Efficiency	$\frac{12500}{13539}$	=	92.4%

Fig. 42 shows the Efficiency vs Load current



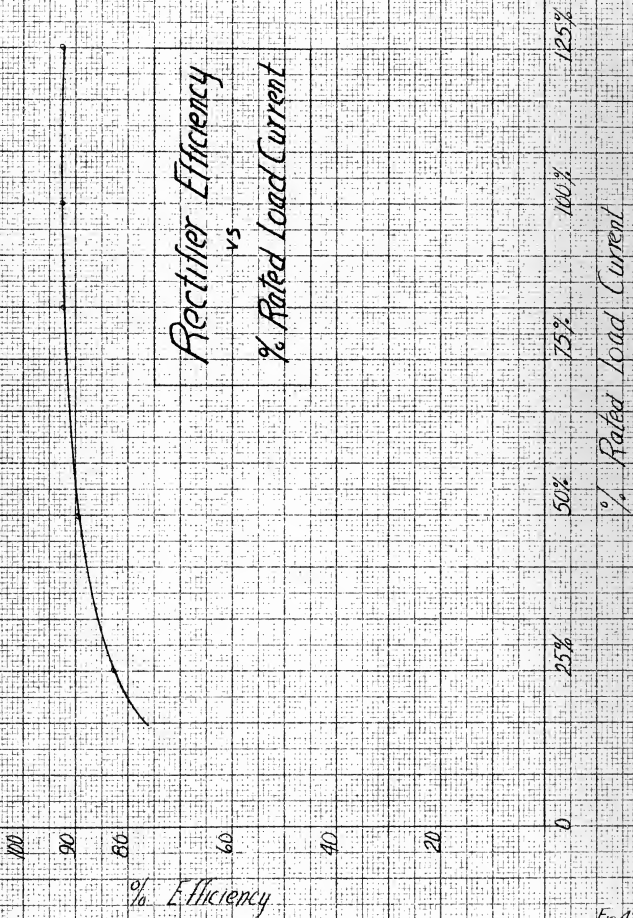
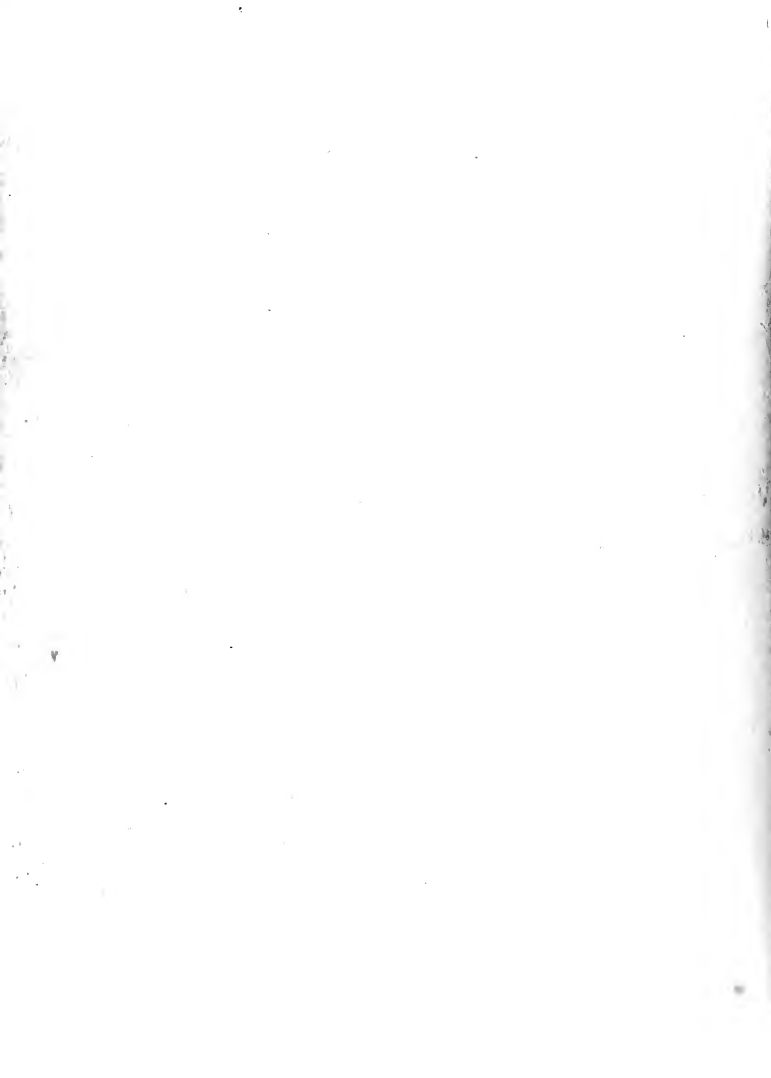


Fig 42





#### 4. Power Factor

One of the disadvantages of the mechanical rectifier is its low power factor. Koppelman (2) stated that the power factor would vary from an optimum of .92 with perfect iron to a minimum of .85 with poor iron. This can be readily determined theoretically since the power factor is one minus the ratio of the reactive voltage drop to the maximum output voltage. For this unit, the base load power factor will be for 115 volts output,  $1 - \frac{25.4}{140.4}$  or .82. This will improve as the load is increased and the magnetic delay is increased to a maximum at full load of  $1 - \frac{20.8}{140.4}$  or .85.

The power factor could be improved slightly within the limitation imposed by the theoretical limit but only at the expense of increased weight of the core.



## CHAPTER VIII

### OPERATION

#### 1. Contact timing.

The original lining up of the rectifier will require an oscilloscope as was mentioned before in Chapt. V. It is extremely important that it be carefully done since the entire operation of the rectifier depends upon the correct timing. This would have to be checked periodically as experience will dictate, as routine preventive maintenance. It is difficult to make any estimate of the maximum time between checks since no such mechanism has ever been run. However, judging on the basis of experience at 60 cycles and dividing by 7, the contacts should run at least 250 hours before any adjustment would be required.

#### 2. Starting and Stopping.

This unit can be started very simply. The contacts will already be operating and will be synchronized by the gearing. Pre-excitation will be operating since it is presumed that this circuit will always be connected to the AC line with only circuit breakers in the line. There is no assurance that the AC voltage will be applied to the main windings in exactly the right relation to the magnetic condition of the cores existing at the last shut down. To reduce transients and avoid possible flash overs, it is necessary to first insert in the circuit, current limiting resistors which will limit the current to a maximum value of the base load plus DC pre-excitation, and reduce the



applied voltage to approximately half. These resistors need be in the circuit for only a few cycles to insure that rectifier is operating properly before rated voltage is applied.

Also, there should be some sort of interlock with the DC side, to insure that the AC switch can never be opened without first opening the DC switch. This is necessary to prevent inverter action during stopping if there are any active loads on the line. (Batteries, etc.) Also, it should not be possible to close the AC switch unless the DC switch is open. This will prevent overloading the current limiting resistors during starting and reduce the transients.

These requirements will require a three phase switch with two sets of contacts, one set of which closes about a half a second or less before the other set which will be the main contacts. This switch must also be connected by an interlock with the DC switch as outlined before.

The resistors for this circuit can be determined with the following analysis:

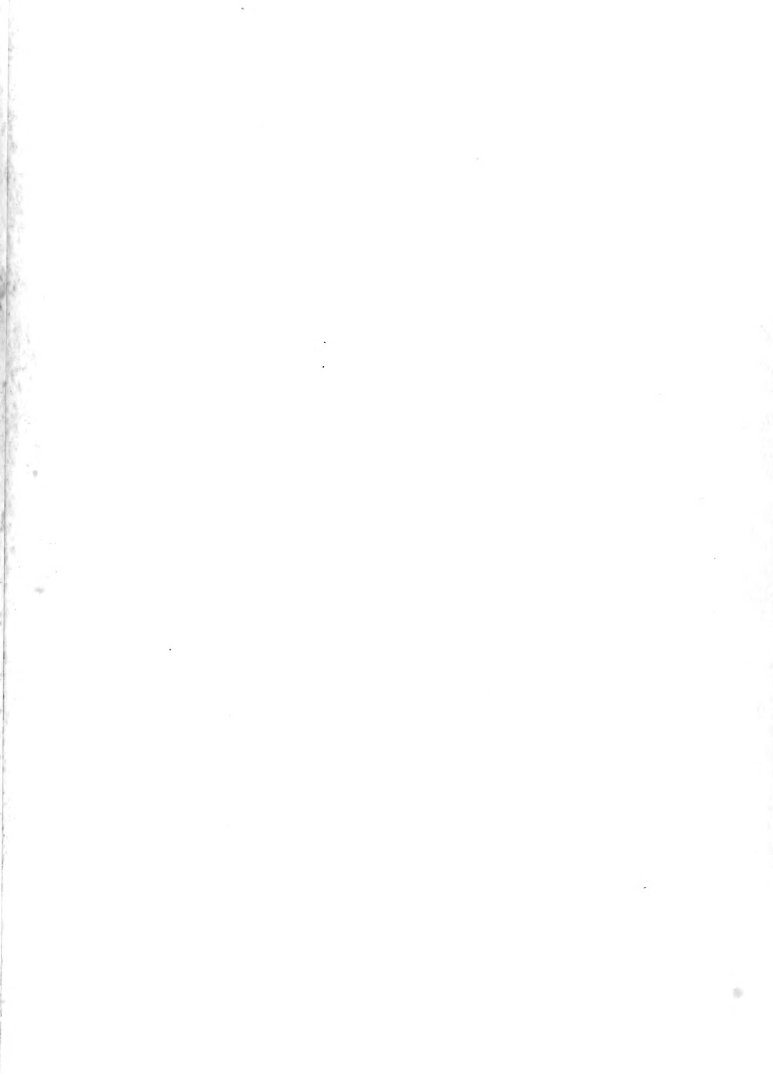
$$I_{\text{Base Load}} = .65 + .815 = 1.46 \text{ amps.}$$

$$R = \frac{E_{\phi/2}}{I_{\text{Base Load}}} = \frac{120/2}{1.46} = 42 \Omega$$

$$I^2 R = (1.46)^2 \times 42 = 87 \text{ watts}$$



The value of  $I^2R$  need not be made as large as indicated since it will conduct for an extremely short period. If we arbitrarily reduce the value by a factor of 10, we should use a 39 ohm, 10 watt resistor.





## CHAPTER IX

### CONCLUSIONS

This has been an attempt to design conservatively a mechanical rectifier which could be used in large aircraft. The frequency is so much greater than anything previously used that it was necessary to design with only the fundamentals as a basis. The results obtained were in many respects, better than had been expected when the design was originally begun.

The weight for a given input and output voltage is a direct function of the line to line short circuit impedance of the power source. This means that the source must be of large capacity, the larger the better. The optimum would be a normal power line with an impedance of practically zero.

The weight could undoubtedly be reduced after one unit has been built and tested. Many parts of this design were based on an assumed optimum solution to a complex problem. The whole core problem should be investigated separately. This design considered only one value of  $2W/d_m$ , and only one ribbon thickness. These assumptions were undoubtedly not an optimum for both hysteresis loop size and minimum inductance. A thicker ribbon might give very little more loss and decrease the cross sectional area of the core and so lower the inductance of the coil. This would in turn, reduce the weight of the core. The minimum weight of the core was limited by the low voltage



limit of 115 volts. Experience might dictate that it was not necessary to have this much IR drop to the bus bar. Also, the line to line short circuit impedance of the source may well prove to be much smaller than the value used.

This design gave a weight of 3.20 pounds per kilowatt and an efficiency ranging from 82.7% at 1/4 load to 92.1% at rated load. The entire unit could be put in a space 9 inches x 9 inches x 15 inches.

This type of rectifier has numerous advantages over any other system envisioned. The voltage control system is very simple. The ambient air temperature will not be a problem until it reaches at least 100°C. The most critical item is the hot spot temperature of the core which should be kept below 250°C. The copper of course is completely exposed to the air. Cooling air could be taken from the supply of the alternator. ITE designs 200 ampere units with no forced cooling.

This system also has definite disadvantages; while it is not particularly sensitive to voltage and frequency fluctuations, it is mechanically sensitive during operation. This is the case because the contact timing should be kept as close to the design value as possible. The safety step will permit some leeway in the opening time, but an error in the closing time will either result in a momentary current reversal as the contact closes or a reduction in voltage at rated load. The power factor is also a disadvantage. It will never be better than .85 at any load.



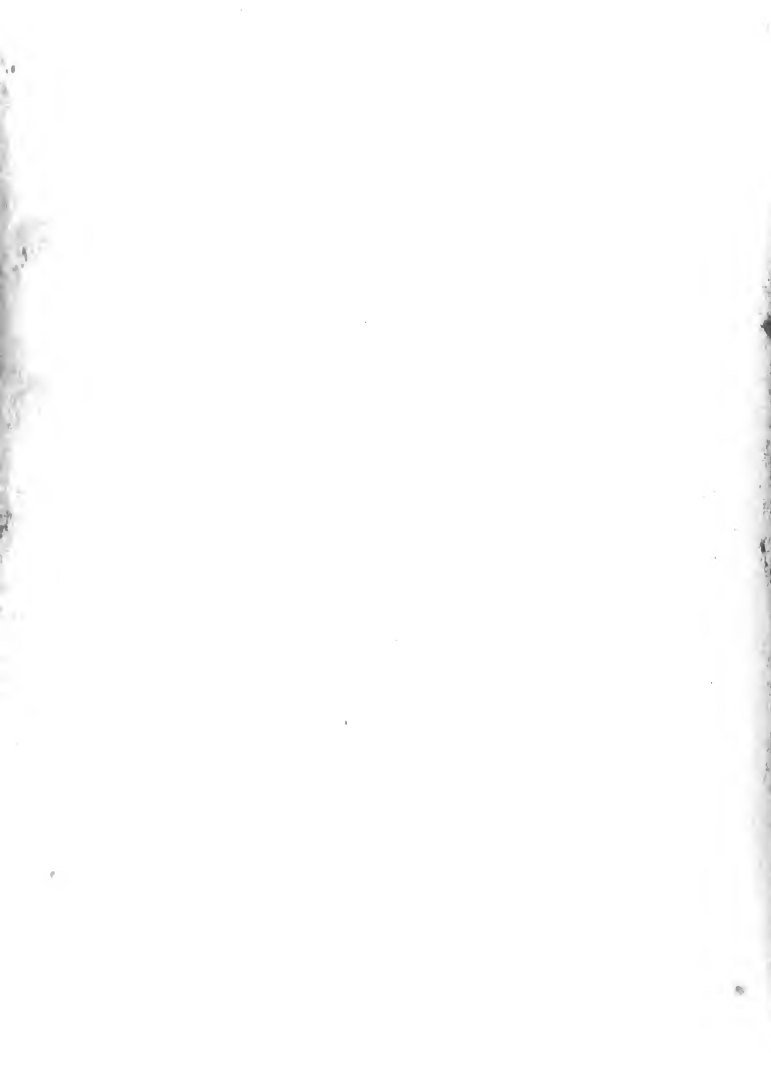
This author has no weight data on other types of rectifying systems at this voltage and so no comparison can be made. However, the fact that the system is not altitude nor temperature sensitive is a tremendous advantage.

This should be a good solution for the rectification problem in general for large aircraft. It should be an excellent solution for large aircraft flying at high altitudes or where high ambient air temperature has become a problem.



## BIBLIOGRAPHY

1. Jensen, O. Final Report on the Contact Converter  
Submitted to US Navy Bureau of Ships, Contract  
NObs 28577 by ITE Circuit Breaker Co.
2. Koppelman, F. Electrotechnical Principles of the  
Mechanical Rectifier; English translation and  
photostats of the original series of articles  
in Electrotechnik und Maschinenbau, Nos. 17,  
18, 35, and 36, 1942; Dept. of Commerce PB 80932
3. Rolf, E. The Computation of Mechanical Rectifier In-  
stallations, ITE Circuit Breaker Co., For Bureau  
of Ships, NObs 28577, June 30, 1949
4. Park and Robertson The Reactance of Synchronous  
Machines, AIEE Quarterly Transactions of Feb.,  
1928, Vol47, No. 2, April, 1928
5. Papers Presented at the NOL Magnetic Materials  
Symposim, NOLR 1091 , 15 June 1948
6. Koppelman, F. Appendix 14 to PB 80932, Original  
"Verfahren Zur Messung Annähernd Rechteckiger Mit  
Von Ringkern", Archiv für Elektrotechnik, Vol38,  
No. 4, 1944





## APPENDIX I

### EXPERIMENTAL DETERMINATION OF THE CORE CHARACTERISTICS

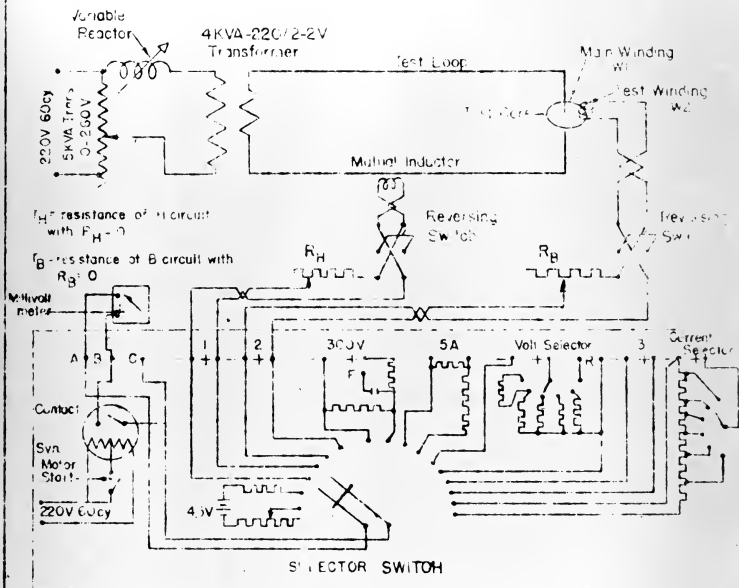
The Vectormeter is the most accurate method known to obtain the dynamic hysteresis loop under conditions approximating those found in a mechanical rectifier. This loop combines the resultant of the hysteresis loop proper and the eddy current effects.

The complete circuit diagram is shown in Fig. A43. Only connections 1 and 2 of the Vectormeter were used in this particular application. The test loop shown in Fig. A 44 is 50" x 37" and can be broken to insert the test core. The loop used at NOL has a small bar which is used on the test side to accommodate the small test cores used there. The Mutual Inductor can be seen on the top of the loop and has a mutual inductance of  $6.88 \mu h$ . This is used as a pick up for measuring the value of  $H$ . The winding on the test sample consisted of 225 turns and was used to pick up the change in  $B$ . Fig. A45 is a top view of a Vectormeter being offered by ITE which closely resembles, in external appearance, the German model used in this determination.

The operation of this device is extremely simple after it has been calibrated. The voltage required to give the desired step length can be calculated by the formula given in the report:

$$E = \frac{A_{Fc} \Delta B \times 10^{-4}}{\sqrt{2} \times \Delta T \times 10^{-3}}$$

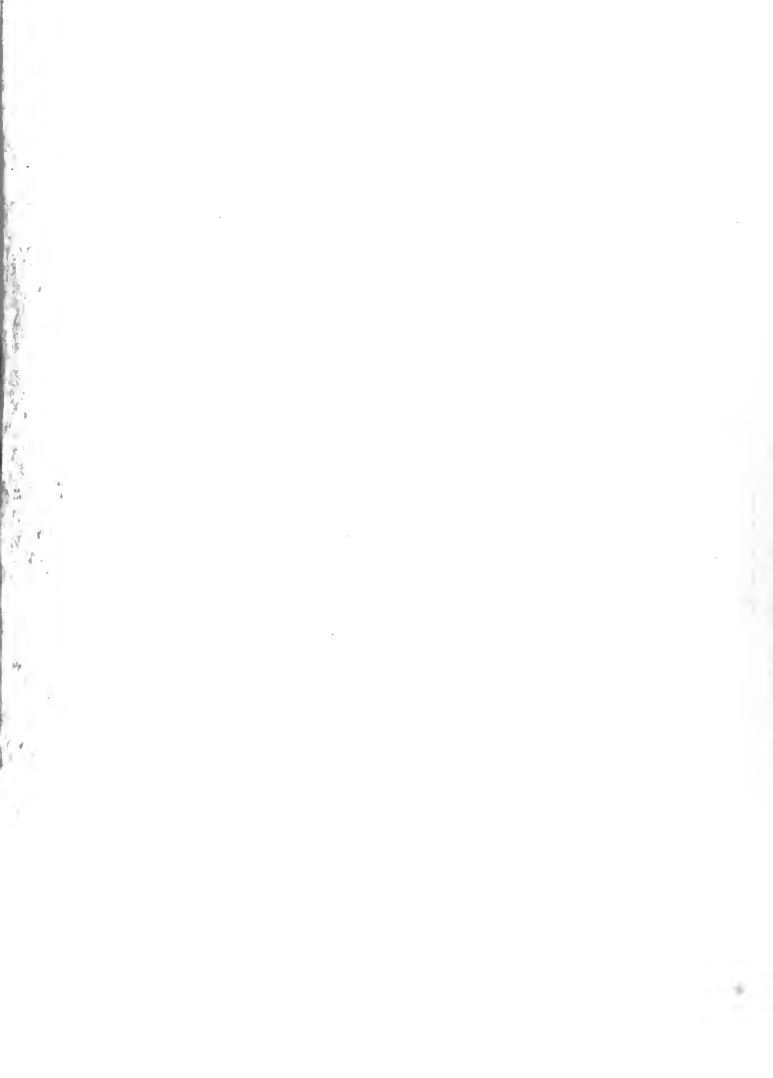




AEG (1947) VECTORMETER  
 property of  
 BUREAU OF SHIPS

FIG. A43

THE TEST CIRCUIT FOR MEASURING  
 MAGNETIZATION AND COMMUTATION  
 CURVES OF CORE MATERIAL



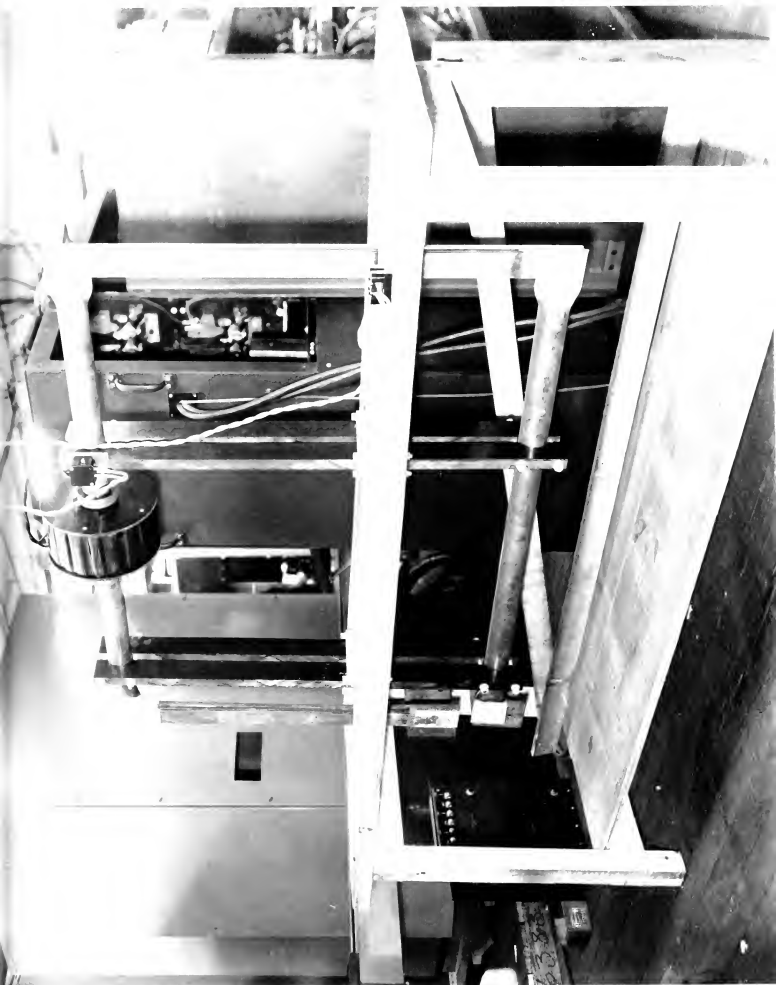
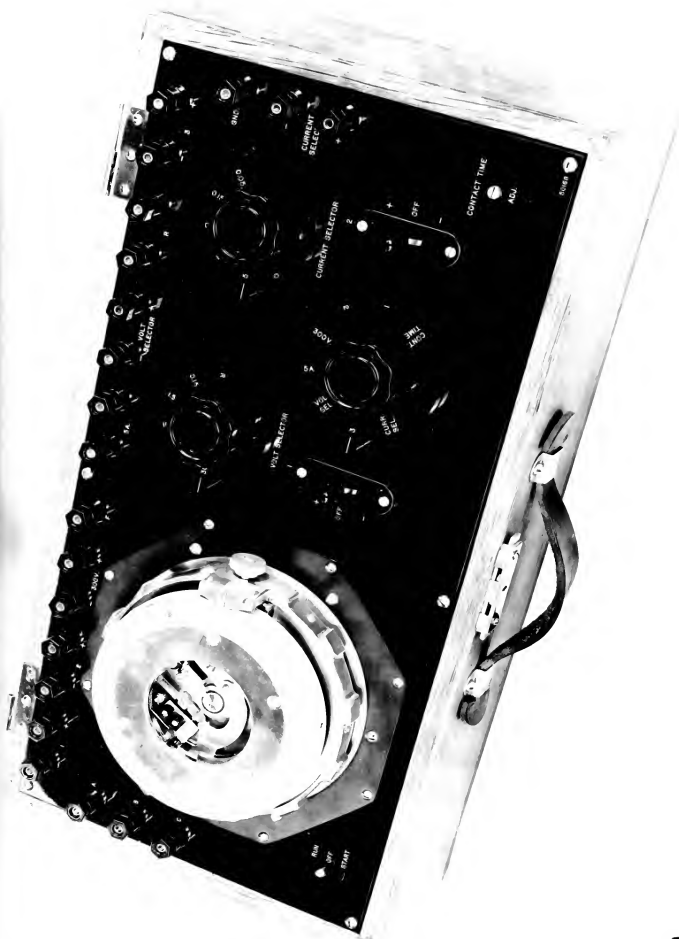


Fig A 44  
99

hbc-W







The calculated voltage, corrected for the transformer turns ratio, can be most conveniently read across the primary of the transformer for these small cores. This also gives a constant check on the input voltage fluctuations which were very annoying during the tests at NOL. ITE has found it necessary to use a separate supply for their Vectormeter. This problem should be very carefully considered if any new installations are contemplated since the equipment is very sensitive to even minute voltage fluctuations, in the region of the step.

The Vectormeter proper is a small single phase mechanical rectifier. The contact is gold and is set so that it is open exactly  $180^{\circ}$  and closed the same amount. The entire contact mounting can be rotated relative to the synchronous driving motor so that the opening and closing time can be varied from  $0^{\circ}$ - $360^{\circ}$ . The millivoltmeter averages the output of the rectifier and by proper calibration, will read  $\beta$  and H directly.

As an example, if a sine wave is applied to either terminals 1 or 2, a maximum reading will be obtained on the voltmeter when the contact is opening and closing at  $0^{\circ}$  and  $180^{\circ}$  respectively. Conversely, it will read zero when the contact is opening and closing at  $90^{\circ}$  and  $270^{\circ}$  respectively.

The following derivation should make the theory of operation clear. If further information is desired, the original article on the subject by Koppelman is Ref. (6).



For convenience, the following is a tabulation of the symbols used in this derivation and their values for this equipment.

N	No. of turns of magnetization winding (1)
n	No. of turns of test winding (225)
$r_o$	Resistance of millivoltmeter 10 ohms
$R_B$	Adjustable non-inductive resistor in flux test circuit (ohm)
$R_H$	Ditto, current test circuit (ohm)
$r_B$	Resistance of test coil and all leads in flux test circuit. 1.3 ohms
$r_H$	Resistance of mutual inductor coil and all leads in current test circuit 3.3 ohms
$A_c$	Iron cross section of core under test .205 (sq.cms.)
$l_m$	Mean length of core (cms) 14.46
f	Frequency of test circuit (60) (Cycles/sec)
$e_B$	Millivoltmeter reading, flux test
$e_{B_o}$	Full scale millivoltmeter reading, flux test (2 mv)
$e_H$	Millivoltmeter reading, current test
$e_{H_o}$	Full scale millivoltmeter reading, current test (2 mv)
$E_B$	Average value of voltage on test winding
$E_H$	Average value of voltage in mutual inductor
M	Mutuel inductance $6.88 \mu h$ (micro henries)
$B_o$	Flux density change
$B_m$	Flux density
H	2 $H_o$
$H_o$	Magnetmotive force



# A. Calculation of $R_B$

The instantaneous value of  $e_B$  is:

$$e_B = n A \frac{d\beta}{dt}$$

or multiplying and dividing by  $f$  and integrating

from  $0^\circ$ - $180^\circ$

$$\Delta\beta = \frac{f \int_0^{180} e_B dt}{fn A_c}$$

This operation is performed by the Vectormeter. The average reading of the voltmeter will be:

$$E_B = e_B \frac{r_o + r_B + R_B}{r_o}$$

or

$$E_B = f \int_0^{180} e_B dt$$

This gives:

$$\Delta\beta = e_B \frac{r_o + r_B + R_B}{r_o fn A}$$

or

$$R_B = \frac{fn A \Delta\beta}{e_B} r_o - (r_o + r_B)$$

To calibrate this unit for ease in reading, if we take 20 kilogauss for maximum deflection,  $R_B$  becomes:

$$R_B = fn A r_o \frac{\Delta\beta_o}{e_{B_o}} - (r_o + r_B)$$

Substituting the values for the core used and this circuit, the final result was:

$$R_B = \frac{60 \times 225 \times .205 \times 10 \times 2 \times 2.0 \times 10^{-4}}{.2 \times 10^{-3}} - (10 + 1.3)$$

$$= 5531.3 \Omega$$

B can now be read directly from the millivoltmeter in kilogauss from 0 to 20 kilogauss.



## B Calculation of $R_H$

In a similar manner to A.

$$e_H = M \frac{di}{dt}$$

Where  $i$  is the instantaneous magnetizing current

As before:

$$\Delta i = \frac{\int \int_0^{i_0} e_H dt}{fM}$$

$$E_H = e_H \frac{r_0 + r_H + R_H}{r_0} = \int \int_0^{i_0} e_H dt$$

Considering now ampere turns per inch

$$\Delta H = \Delta i \frac{N}{l_m}$$

This makes  $\Delta H$

$$\Delta H = \frac{N e_H (r_0 + r_H + R_H)}{f l_m r_0}$$

or

$$R_H = \frac{\Delta H f M l_m r_0}{e_H N} - (r_0 + r_H)$$

Again for calibration:

$$R_H = \frac{f M l_m r_0}{N} \frac{\Delta H_0}{e_{H_0}} - (r_0 + r_H)$$

This data was taken in oersteds with 2 and 20 oersteds maximum deflection on low and high scale. The resulting values were:

2 oersteds

$$R_H = 60 \times 6.88 \times 10^{-6} \times 14.96 \times 10 \times \frac{2 \times 2 \times 2.02}{2 \times 10^{-3} \times 2.59} - (10 + 3.3)$$

$$= 81.5 \text{ ohms}$$

20 oersteds

$$R_H = 10 \times 94.8 - 13.3 = 935 \text{ ohms}$$





These calculated values set on the correct decade  
Boxes gave the hysteresis loops used in this report. The  
curves taken but not used in the report proper are  
included in this Appendix for reference.

The data on the test core was:

NOL core 847X

ID - 1 5/8" OD 2"

190 turns .0006" x 1/4" ribbon with magnesium oxide  
insulation

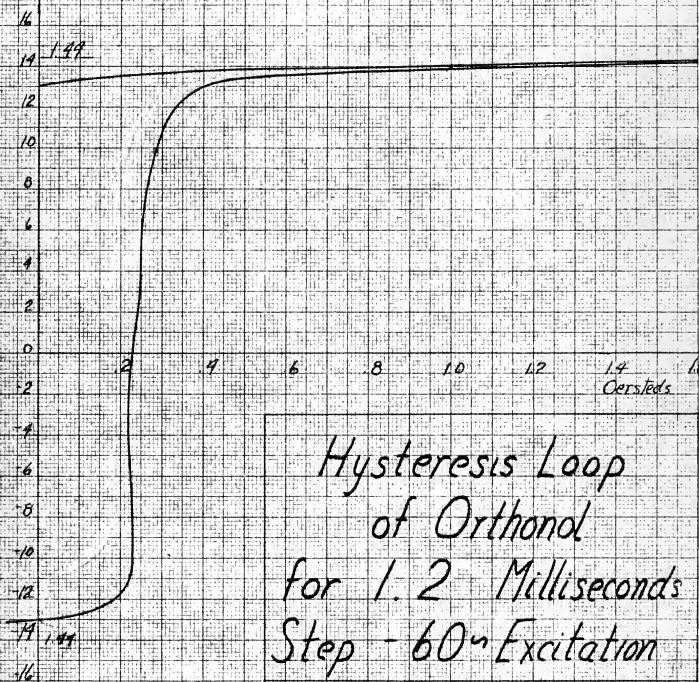
Weight 24.4505 gms Specific gravity 8.25,  $A_{Fe}$  - .205 cms.

Test windings - 225 turns and 125 turns

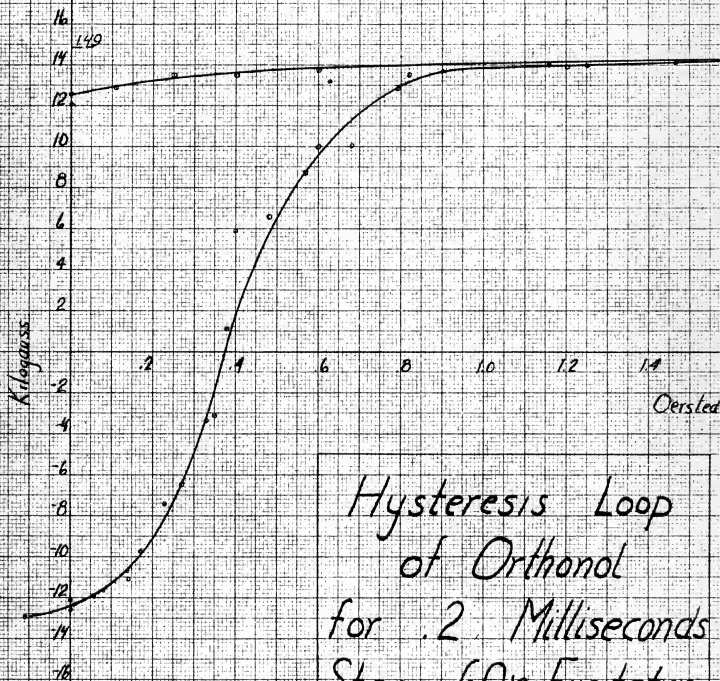
Heat treatment- 1200°C for 2 hours followed by rapid  
cooling. 300°C for 18 hours in 87.2 oersted field  
followed by rapid cooling in no field.

The hysteresis loops for 60 and 400 cycles were compared  
with the circuit shown below. The step length was determined  
by calculating the ratio of step length to a full cycle length.  
This was obtained by varying the input voltage until the  
correct length was obtained. All circuit constants were  
unchanged, the change from 60 to 400 cycles was accomplished  
with a two pole, double throw switch. The resulting hysteresis  
loops were taken from the surface of the tube with tracing  
paper.





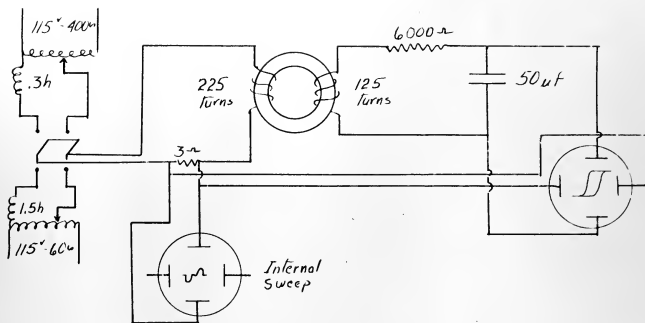




Hysteresis Loop  
of Orthonol  
for .2 Milliseconds  
Step 60~ Excitation

$$\Delta T = \frac{92^\circ - 87.5^\circ}{21.6^\circ} = 2 \text{ msec}$$





Circuit for Comparing 60 and 400 cycle hysteresis Loops

Fig A48





## APPENDIX II

### EXCERPTS FROM F. KOPPELMAN'S PAPER ON THE MECHANICAL RECTIFIER

This is an excerpt from Appendix 13 of the Dept. of Commerce publication PB 80932 as described in the Bibliography. It was included to show the derivation of the Koppelman's (2) basic formula for step length.

The German nomenclature is relatively difficult to understand without considerable study. The following list of German symbols and their English equivalents as used in the paper are included to simplify reading the Appendix.

$$J = \beta \cdot B - \mu \cdot H$$

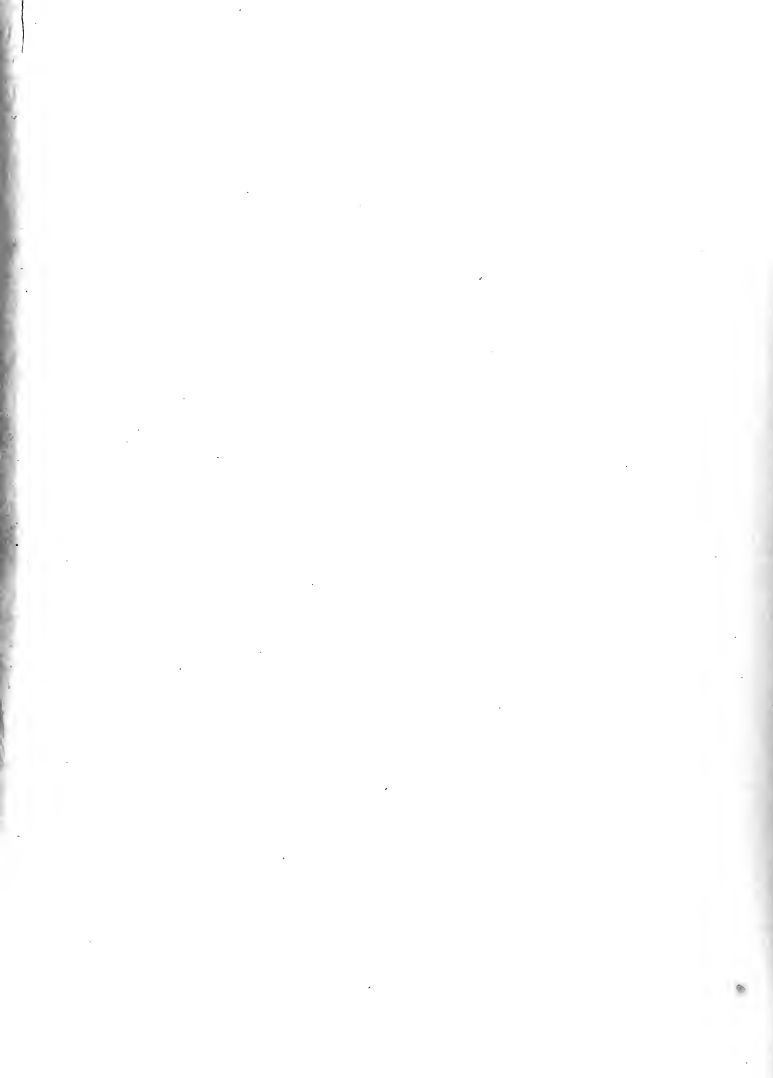
$I_{gl_0}$  - I base load

$I_{gl_{max}}$  - I maximum overload

$I_{gl_{nenn}}$  - I rated load

$t_{ein}$  - closing moment

$t_{aus}$  - opening moment



ELECTROTECHNICAL PRINCIPLES OF THE MECHANICAL RECTIFIER(CONTACT CONVERTER)

(Part 1)

by F. Koppelman - Berlin

NK 621.314.5 : 621.316.543

**Summary:** This paper serves the purpose of enabling the reader to form an opinion of the quantitative question of the contact converter. The relation between short circuit voltage, size of choke coils, overload capacity and backfire safety is presented in Part 1. Other questions regarding the calculation of load-factor and efficiency will be dealt with in a later paper.

The contact converter is a mechanical rectifier. It was first reported before the VDE Berlin 17. September 1940. It has been built for voltage from 30 to 600 volt DC. and for loads up to several 1000 kw. Its advantage over other conversion means is its great efficiency. Its function and calculations are somewhat different from those of machine converters or mercury arc rectifiers.

A presentation of the electro-technical fundamentals of the contact converter might, therefore, be of interest. This paper treats this theme as the first of a series of contemplated discussions.

The performance of the contact converter, which has been described in a former paper, is briefly summarized here. The current interruption in the disconnected phase, which occurs at each current directive change, is accomplished in rotating machines by the commutator bar leaving the edge of the brush. In the Mercury arc rectifier, this interruption is accomplished by a medium which is non-conducting in the reverse direction. This is accomplished in the contact converter by means of a mechanical breaker with metallic pressure type contacts having openings of only a few millimeters, and driven by an eccentric. The arcing of the contacts, which up to now has been a difficult problem to solve in mechanical rectifiers for large currents, has been eliminated by switching chokes having a saturable core, in the contact circuit during the working time of the particular phase. In other words during the time this phase will carry current and is saturated, but is capable on current reversal of the phase to delay the current reversal sufficiently to permit contact opening.

During this time, it is merely the magnetizing current of the switching choke that flows in the relieved phase, which is kept at a minimum by use of special high grade iron cores. The contact can, therefore, aided by a parallel condenser, interrupt this current without arcing even at high leading current, as the magnetizing current is independent of the load current, provided the opening moment of the contact occurs at the time interval during which the associated choke coil is unsaturated. The purpose of this paper is to outline the quantitative investigations, under which this condition prevails. It proves that these calculations, as well as others, which will be treated later, can be made even with sloping magnetization curves of the choke coil iron cores.

### 1. The Magnetization of Choke Coil During Contact Opening

We start with the magnetization of the choke coil core in the current giving off phase and at the moment that the contact is opened in this phase. If this magnetization is smaller than the saturating magnetization, then only the low dischargeless, disconnectable, magnetizing current of the choke flows through the contact at the instant of opening.



## 1. The Remagnetization of Shoke Coil During Contact Closing

We start with the magnetization of the shoke coil core in the current giving off phase and at the moment that the contact is opened in this phase. If this magnetization is smaller than the saturating magnetization, then only the low dischargeless, disconnectable, magnetizing current of the shoke flows through the contact at the instant of opening.

The contact of phase 2 is closed in the moment  $t_{on}$ , and takes over the current of phase 1 (fig. 1 and 2). At this moment, phase voltage  $e_2$  is already greater than phase voltage  $e_1$ . Then, as with the mercury arc rectifier, the current in phase 1, is suppressed by the closing of 2. (fig. 2). With a mercury arc rectifier, the current decreases to zero, when the valve action prevents reversal of current from originating in phase 1. With the contact converter there is a somewhat similar action: The shoke coil 1, which until then was saturated in the direction of the load current, does not prevent the current to reach zero, as it practically remains saturated. The magnetization curve of the shoke coil iron (fig. 3) shows that, when the current in 1 has reached a small negative value  $J_0$  on the upper knee of the magnetization curve, a further rapid current decrease is prevented until shoke 1 has reached the magnetization  $J_0$  on the lower magnetic knee. Before that, contact 1 has to open for instance at time interval  $t_{off}$  (fig. 2.)

We will call the current flow during the remagnetization from  $J_0$  to  $J_1$ , that is between the time interval  $t_1$  and  $t_2$  (fig. 2). The mean of the current; the time interval  $\Delta t = t_2 - t_1$ ; the change; the change of magnetization  $\Delta J = J_1 - J_0$  (for the step) magnetization change. We will discuss later an exact definition of  $J_0$  and  $J_1$  which is the beginning and the end of the step. It is sufficient to establish here that  $J_0$  at the beginning, and  $J_1$  at the end of the step is located at the decrease of the magnetization curve, or is between the upper and lower knee of the magnetization curve. It follows from the above described short circuit of phase 1 and 2, if the ohm resistance is disregarded and the direct current is held timely constant through the shoke coil that:

$$\frac{dJ}{dt} = - \frac{e_2}{L}$$

and for the short circuit formed via contacts 1 and 2 the voltage differential is:

$$e_2 - e_1 = L \frac{dJ}{dt} + R \cdot \left( \frac{dJ}{dt} - \frac{dJ_1}{dt} \right) \quad (1)$$

Here  $L$  is the inductance of the commutation current including air-inductance of the shoke coil<sup>1)</sup>,  $n$  the no. of turns and  $q$  the cross section of shoke coil core. Integration between the limits  $t_{on}$  and  $t_{off}$  gives (fig. 2):

$$\int_{t_{on}}^{t_{off}} (e_2 - e_1) dt = L (J_1 - J_0) + R \cdot (J_1 - J_0) \quad (2)$$

where  $J_0$  is the magnetization of shoke coil core with current  $I_0$ <sup>2)</sup>  
 $J_1$  the magnetization of the shoke coil core 2 in moment  $t_{on}$ , also in

1) Under air-inductance of the core, it is understood to mean the induction the shoke coil would have if it was supplied with a wooden core. Therefore the second sum on the right side of (1) is not to be calculated with the induction  $B$ , but with the magnetization  $I \cdot B$  (H-field-strength).

2) By complete smoothing of the direct current, the magnetization  $J_0$  of shoke 1 is greater (decreasing branch of the hysteresis loop) than that of shoke 2 (increasing branch). It is here understood that  $J_0$  is the arithmetic average of the two values.



contact 2, and Jaus the unknown magnetization of core 1 in the time moment  $t_{aus}$  of the opening of contact 1.

Formula (2) shows that the unknown magnetization Jaus is so small, (so near the negative saturation) that the greater value of the integral of the current change voltage is between  $t_{ein}$  to  $t_{aus}$ . In other words the later, at fixed  $t_{ein}$ , the break time moment  $t_{aus}$  lies, it also becomes less, with a smaller product  $I_{gl} \cdot L$ , that is at no load, a lesser part of the step length  $t$  of the choke coil lies behind the opening time moment  $t_{aus}$ , than at a full load (fig. 4).

## 2. The Greatest Possible Load Variation from $I_{gl0}$ to $I_{glmax}$ with Constant Contact Time.

The base formula of the contact converter can be directly derived from Formula 2. The equation is employed, firstly, for the maximum possible current  $I_{glmax}$ , at which the beginning  $t_1$  of the step coincides with the  $t_{aus}$  and secondly for the loading with a lowest current  $I_{gl0}$  which we call a base load. Therefore,  $I_{aus}$  is proportioned with  $I_{glmax}$  and  $I_{gl0}$  if the DC current is completely saturated.

$$\int_{t_{ein}}^{t_{aus}} (e_2 - e_1) dt = L \cdot I_{glmax} + nq(J_{1max} - J_{ein} + J_{1max} - J_0^*) \quad (3)$$

$$\int_{t_{ein}}^{t_{aus}} (e_2 - e_1) dt = L \cdot I_{gl0} + nq(J_{10} - J_{ein0} + J_{10} - J_0^*) \quad (4)$$

Therefore we have the magnetization Jaus, in the case of loading with base load current  $I_{gl0}$  designated with  $J_0^*$ . For  $I_{gl} = I_{glmax}$  according to the definition of  $I_{glmax}$   $t_{aus}$  lies at the beginning of the step and is defined by magnetization  $J_0^*$ . As the left side of (3) and (4) are equal it follows that<sup>4)</sup>

$$L \cdot I_{glmax} + nq(J_{1max} - J_{ein} + J_{1max} - J_0^*) = L \cdot I_{gl0} + nq(J_{10} - J_{ein0} + J_{10} - J_0^*) \quad (5)$$

or:

$$L(I_{glmax} - I_{gl0}) + nq[(J_0^* - J_0) - (J_0^* - J_0) - 2(J_{1max} - J_{10}) - (J_{ein0} - J_{ein})] \quad (6)$$

and when the right side is multiplied with  $\Delta J_0 = (J_0^* - J_0)$

$$nq \Delta J_0 = \frac{L(I_{glmax} - I_{gl0})}{(1 - \sigma - \gamma - \delta)} \quad (7)$$

by shortenings:

$$\sigma = \frac{J_0^* - J_0}{\Delta J_0} \quad (8)$$

$$\gamma = \frac{2(J_{1max} - J_{10})}{\Delta J_0} \quad (9)$$

$$\delta = \frac{J_{ein0} - J_{ein}}{\Delta J_0} \quad (10)$$

$\delta$  is a value which normally is small, while  $J_{ein}$ , in axis of the usual contact converter is only altered slightly. It therefore follows that in order to simplify  $\delta = 0$  if the value  $\delta$  is zero, when the magnetization above  $J_0$  is not increased with increased current, then we have an ideal iron for a contact converter.

<sup>4)</sup> This demands, that L comprises all inductive resistances up to the voltage sources in the right manner, which will be spoken of in a later work, furthermore that all voltage drops up to the voltage-sources must be neglected.





Of special importance is the value  $\sigma$ . From (8)  $\sigma = 0$  for  $J_0 = J_0$  and  $\sigma = 1$  for  $J_0 = J_0$ .  $\sigma$  is therefore that fraction of the total demagnetization  $\Delta J_0$  of the core, which with base load  $I_{cl0}$  lies behind the break point of the associated contact. This fraction  $\sigma \Delta J_0$  serves to show, at a later time, whether to make the voltage at the separating contact small or at suitable re-excitation of the choke, zero or positive. The greater  $\sigma$  is, the earlier is the interruption against backfire. We call the fraction  $\sigma \Delta J_0$  at the step, the no load safety. The reciprocal fraction  $(1 - \sigma) \Delta J_0$  of the step makes possible the load change between the limits  $I_{clmax}$  and  $I_{cl0}$ . From (7) this is greater, the smaller the inductance  $L$  in the commutation current is. While at max. load, nearly the whole voltage integral of the current reversal voltage is used to change the current in the induction  $L$ . A large part of this voltage integral remains free at a small load and lays itself on the choke coil of the opening phase and depresses the magnetization.

### 3. Definition of the Step-length $\Delta t_0$ Referred to the Max. Value of Current Change Voltage.

Before formula (9) will be discussed, it will be transposed. On the left hand side stands a product, which characterizes the size of choke coil, namely the product of number of windings, iron cross-section and for the step useful magnetization-change  $\Delta J_0$ . If on one of  $J_0$  magnetized choke coil, a constant voltage  $U$  has been laid, the result, after using the induction law, will be:  $U = nq \frac{\Delta J_0}{\Delta t}$ , the time  $\Delta t$ , in which the magnetization under the influence of voltage  $U$  is changing from  $J_0$  to  $J_0$ , that is  $\Delta J_0$  or

$$\Delta t = \frac{\Delta J_0 \cdot nq}{U} \quad (11)$$

Step-length based upon the "max. value" of the current change voltage is defined as the demagnetization time  $\Delta t_0$  of the choke coil under the max. value of current change voltage. If  $X$  is the effective value of phase voltage, then at 3-phase bridge-connection

$$\Delta t_0 = \frac{\Delta J_0 \cdot nq}{\sqrt{2} \sqrt{3} \cdot X} \quad (12)$$

The calculation with this formula is easy and clear, as will be shown in the following.

### 4. Main Formula for the Calculation of the Choke Coil in 3-phase Bridge Connection

With (12) we obtain from (7)

$$\Delta t_0 = L \frac{(I_{clmax} - I_{cl0})}{\sqrt{2} \sqrt{3} \cdot X (1 - \sigma - \gamma)} \quad (13)$$

We assume  $\sigma$  as well as  $I_{cl0}$  being neglectable in (13) and call  $I_{clmax} = U I_{clmax}$ , that is, we express the highest current as multi-le value  $U$  (overload-capacity) of the rated current,

$$t_0 = \frac{L \cdot U I_{clmax}}{\sqrt{2} \sqrt{3} \cdot X (1 - \sigma - \gamma)} \quad (14)$$

In this formula, the inductive short circuit voltage,  $\delta$ , will be inserted

$$\delta = \frac{0.5 \omega L I_{clmax}}{X} \quad (15)$$

5) The formula (13) also will be reserved in this simple form for other than 3-phase bridge connections. The inductive potential drop will later replace the short circuit voltage  $\delta$ , for 3-phase bridge connection  $\gamma = 0.5$ . Hence:

$$\Delta t_0 = \frac{L \cdot U}{\omega (1 - \sigma - \gamma)} \quad (16a)$$



(0.5 L = inductivity of one phase  $\omega = 2\pi f$ ). Hereby is  $I_{\text{eff}}$  the effective value of the secondary rectifier current. As it is known, it will be, by 3-phase bridge connection, neglecting the little influence of the finite current change time

$$I_{\text{eff}} = \sqrt{\frac{2}{3}} I_{\text{eff, max}} \quad (16)$$

Also

$$\varepsilon = \frac{\omega L I_{\text{eff, max}}}{\sqrt{3} \sqrt{2} \sqrt{2}} \quad (17)$$

resulting out of (14) by complete smoothed DC<sup>7)</sup>

$$\Delta t_s = \frac{\varepsilon \cdot U}{\omega (1 - \sigma - \eta)} \quad (18)$$

This principle formula, for the theory of contact converters, will be discussed in the following.

### 5. Example for the Use of the Basic Formula for the Standlength

Formula (18) is first illustrated by a practical example:

It is desired to find the (related) steplength  $\Delta t_s$  of choke coils for a converter, which shall, for a short time carry an overload of double the amount of current, but the time point of connection  $t_{\text{conn}}$  shall not fall outside of the step, that is  $\xi = 2$ . The defined (15) inductive short circuit voltage amounts to 7%, that is  $\xi = 0.07$ . The frequency of DC is 80, that is  $\xi = 314$ . The magnetization at highest current  $0.1 I_{\text{eff, max}}$  is ascertained from number of turns, for path length and magnetization curve of the choke to be:

$$\begin{aligned} 0.1 I_{\text{eff, max}} &= 1.6 \cdot 10^{-4} \frac{I_A}{\text{cm}} \quad (16,000 \text{ Gauss}), \text{ at smallest current } = \\ &I_{\text{eff}} 1.5 \cdot 10^{-4} \text{ Vs/cm}^2 \quad (6,000 \text{ Gauss}) \end{aligned}$$

Furthermore the usable magnetization for the step is:

$$\Delta J_s = 2.5 \cdot 10^{-4} \text{ Vs/cm}^2 \quad (25,000 \text{ Gauss})$$

According to formula (9) it follows

$$\eta = \frac{2 (1.6 \cdot 10^{-4} - 1.5 \cdot 10^{-4})}{2.5 \cdot 10^{-4}} = 0.08$$

At no load, or with load of the basic load current  $I_{\text{eff}}$ , with consideration to the safety of contact-opening against backfire, it is required that the re-magnetization of the choke coil will take place for a half after disconnection of the relating contact. Therefore  $\sigma = 0.5$ . The result is according to (18) as follows:

$$\Delta t_s = \frac{\varepsilon \cdot U}{\omega (1 - \sigma - \eta)} = \frac{0.07 \cdot 2}{314 (1 - 0.5 - 0.08)} = 1.06 \cdot 10^{-3} \quad (19)$$

6) In each phase of the converter flow during 2/3 of the DC  $I_{\text{eff}}$  cycle, the effective value of this current is  $\sqrt{\frac{2}{3}} I_{\text{eff}}$ .

7) If the DC is completely smoothed then the approximate situation is:

$$\Delta t_s = \frac{\varepsilon \lambda U}{\omega (1 - \sigma - \eta)} \quad (19b)$$

whereby  $\lambda$  is the proportion of the moment value of DC at beginning of current change, (time point  $t_{\text{ein}}$  in picture 2) to DC average - value.



Winding number and iron cross section of choke coils have to be chosen so that, after (12) the step length under the max. value of the interlocked voltage will amount to about one milli-second, that is  $1/10$  of the part of the curve of the alternating current. By a phase-voltage  $E = 140$  V,  $\delta$  and a winding number  $n = 15$  we obtain for instance after (12) an iron cross section of:

$$q = \frac{\Delta t_s \sqrt{2} \sqrt{3} E}{\Delta J_s n} = \frac{1.06 \cdot 10^{-3} \sqrt{2} \sqrt{3} \cdot 140}{2.5 \cdot 10^{-4} \cdot 15} = 97 \text{ cm}^2 \quad (20)$$

For a small converter it would be chosen for instance  $n = 150$  and iron cross section  $q = 9.7 \text{ cm}^2$ .

#### 6. The No-load-safety

We have called that part of the step, which at no-load lies behind the point of disconnection, the no-load-safety. In the above mentioned calculation example  $\sigma = 0.5$ , that means, only the first half of the step  $\Delta t_s$  was used to obtain a wanted load-capacity-alow-room between  $I_{gl}$  to  $\delta \cdot I_{glmax}$ , the second half to retard the voltage-increase on the opened contact and therewith provide safety against backfiring. If the stepcurrent opened by contact, has the value  $i_{ams}$  (piet. 2), then - (considered that the magnetization of the choke coil is a clear function of the current and not spontaneous, - i.e. no independent magnetization-changings take place) the increase of voltage immediately at contact-opening is

$$\frac{du}{dt} = \frac{i_{ams}}{C} \quad (21)$$

whereby  $C$  is the parallel to the contact lying capacity (piet. 1). For  $i_{ams} = 0.5$  A,  $C = 10 \cdot 10^{-9}$  we obtain for instance  $\frac{du}{dt} = 5 \cdot 10^4$  V/s.

In order to obtain a secure opening of contacts without backfire, the increase of voltage cannot overdraw a certain critical value, for instance  $10^5$  V/s, 10).

If under the pressure of voltage  $e_2 - e_1$ , according to (2), the magnetization  $J_s$  in the choke coil of the relieved phase is reached according to magnetization curve, increasing high current will be permitted to pass. The voltage-increase will become after (21) very much greater than the critical limit of, for instance,  $10^5$  V/s. If the contact opens ahead of this time, are and backfire would occur.

We will mark this part of the step, which lies at no load in the point of time of contact opening, with (piet. 4). The time  $\tau$  can be calculated assuming that, until the end of  $\tau$ , the voltage on the opened contact is small, against the net voltage. Under this assumption, during

- 8) Corresponding to a no-load DC voltage

$$U_{d0} = \sqrt{2} \sqrt{3} \frac{E}{\sqrt{2}} = 2.34E = 328 \text{ V}$$

see for instance Th. Wasserrab, E. and M. 59 (1941) page 3. Calculations at voltage will be taken up in a later work.

- 9) In certain connections, for instance in the so far used 3-phase-bridge-connection with 3 choke coils, the step length  $\Delta t_s$  cannot be very great, for instance not greater than  $1.5 \cdot 10^{-6}$ s. The reason for this will be spoken of in a later work.
- 10) The conditions for wireless connections will be treated in more detail in a later work in connection with known examinations of this subject in the literature.



the time  $T$  the whole interlocked voltage  $e_2 - e_1$  lies on the choke coil of the released phase, as the second choke coil in the current-change-circuit, at this time, is carrying the whole DC. In other words it is practically saturated. As the step current is constant, and under timely conditions changes very little, no voltages lie on the air-conductivity  $L$  of the current-turning-circuit during the time so we obtain out of (1)

$$e_2 - e_1 = nL \frac{dJ}{dt}$$

and by integration between the limits  $J$  and  $J_s$  results

$$\int_{t_{\text{ans}}}^{t_{\text{ans}}^*} (e_2 - e_1) dt = nL (J_s - J) = nL J_s = \sqrt{2} \sqrt{3} \cdot \sigma \Delta_s \quad (22)$$

Out of this formula  $T$  can be calculated.

If the unsaturation of the choke coil takes place from  $J$  to  $J_s^-$  under the max. value of the interlocked voltage, which is almost the case in a direct voltage to zero down-controlled converter, then we have a 3-phase connection:

$$\int_{t_{\text{ans}}}^{t_{\text{ans}}^*} (e_2 - e_1) dt = \sqrt{2} \sqrt{3} \cdot E T_s, \text{ that is after (22)} \\ T_s = \sigma \Delta_s \quad (23)$$

The index  $s$  means, that  $T_s$ , just as well as the whole step  $\Delta t_s$  is based on the max. value of the interlocked voltage and represents the smallest possible value.

If the unsaturation has not taken place from  $J$  to  $J_s^-$  under the max. value of the interlocked voltage,  $T > T_s$ , and out of (23) and (22) with  $e_2 - e_1 = \sqrt{2} \sqrt{3} \cdot E \sin \omega t$ :

$$\cos \omega (t_{\text{ans}} + T) = \cos \omega t_{\text{ans}} - \omega T \quad (24)$$

Out of this formula, any position of the disconnection-time point  $t_{\text{ans}}$  can be ascertained by the tie-up between  $T$  and  $T_s$  (pict. 5). In converters, which are down controlled in voltage, the no load safety  $T_s$  must be sufficiently proportioned for service with smallest DC. A greater safety is then created.

The question arises, how big practically  $T_s$  must be chosen. The choice of  $T_s$  is done by the following points:

1. In order to avoid backfiring by high voltage, it is not sufficient, if in the moment of contact-interruption, the voltage-increase lies for instance below the given critical value of  $10^5$  V/s. Rather, after contact interruption, the interlocked voltage in this moment must be smaller than the flash-over voltage of the interruption length. The flash-over voltage of the contact of known performance with level, sharp edged electrodes is shown in pict. 6, also the fundamental progress over the contact-gap. Below the minimum voltage of air (about 400 V) no flash-over is possible. Even at the smallest gap, at a contact distance of 0.1 mm, that is, at a contact-interrupting speed of 1 m/s  $10^{-3}$ s after contact separation, the flash-over-voltage is about 1,000 V, and in larger converters with usual double interrupting contacts almost 2,000 V.

In order to avoid discharge by connection, contact converters in 3-phase-bridge connection have not been built for more than about 480 V (no-load-voltage  $U_{glo}$ ) in one system. The largest





occurring back-voltage which, in this connection almost equals the interlocked voltage  $\sqrt{2} \sqrt{3} \frac{U}{\sqrt{3}}$ , is thereby smaller than 500 V, as in 3-phase bridge-connection  $U_{glo} = \sqrt{2} \sqrt{3} \frac{U}{\sqrt{3}}$ . With one value  $\tau = 10^{-4}$  s and a contact-interrupting-speed of 1 m/s after the timepoint - a contact-distance of 0,1 mm, and a flash-over-voltage of about 1,000 V for each interruption-distance, will be attained. That is a multiple-security against backfire.

2. If, nevertheless, contact-converters are built in praxis with values which are greater than  $10^{-4}$  s, the reason is, that in practical service, there is an inexactness of contact-times, caused through thermal expansion of the gear, through damage of contact-points during service, or through tolerances during produce and these deviations from the theoretical must be reckoned with. A prolongation of contact-time, i.e. in pict. 4, a shifting of the break-time point  $t_{ms}$  to the right side, means a reduction of no-load safety. In cases of calculatively too small values and even by little differences of the contact times, there is the danger of backfire present, i.e. the converter is mechanically sensitive during service.
3. With this sensitivity to changes of contact-times and by too small no-load safety, a greater sensitivity is also given to certain electrical disturbances of the feeding DC, because, similar to a not wanted prolongation of contact-times, an increase of current-change-voltage also reduces the no-load safety. This is to be seen out of (2), where the enlarging of current-change-voltage (left side of formula) gives a reduction of  $J_{ms}$ . By enlarging the current-change-voltage, the current  $i_1$  (pict. 3) is decreasing faster. According to this fact, the step is beginning earlier, so that the fraction of the step which lies behind the constant break-time-point  $t_{ms}$  is decreasing. An increase of current-change-voltage takes place not only by increase of 3-phase voltage, but partly also by voltage decrease of particular phases. During service of the converter to counter-voltage, the no-load-safety is decreasing if the counter-voltage is getting large in proportion to the produced DC voltage. The DC is then lowered beneath the base load current  $I_{glo}$ , and therewith the magnetization  $J_{ls}$  according to (4) also the magnetization  $J_{\sigma}$ , i.e. according to (8) and the no-load-safety  $\sigma$  according to (23)  $\tau_g$ .

For this reason a no-load safety is given the contact-converter at low voltage, which may under circumstances amount to values several times that which is necessary considering the flash-over-voltage.

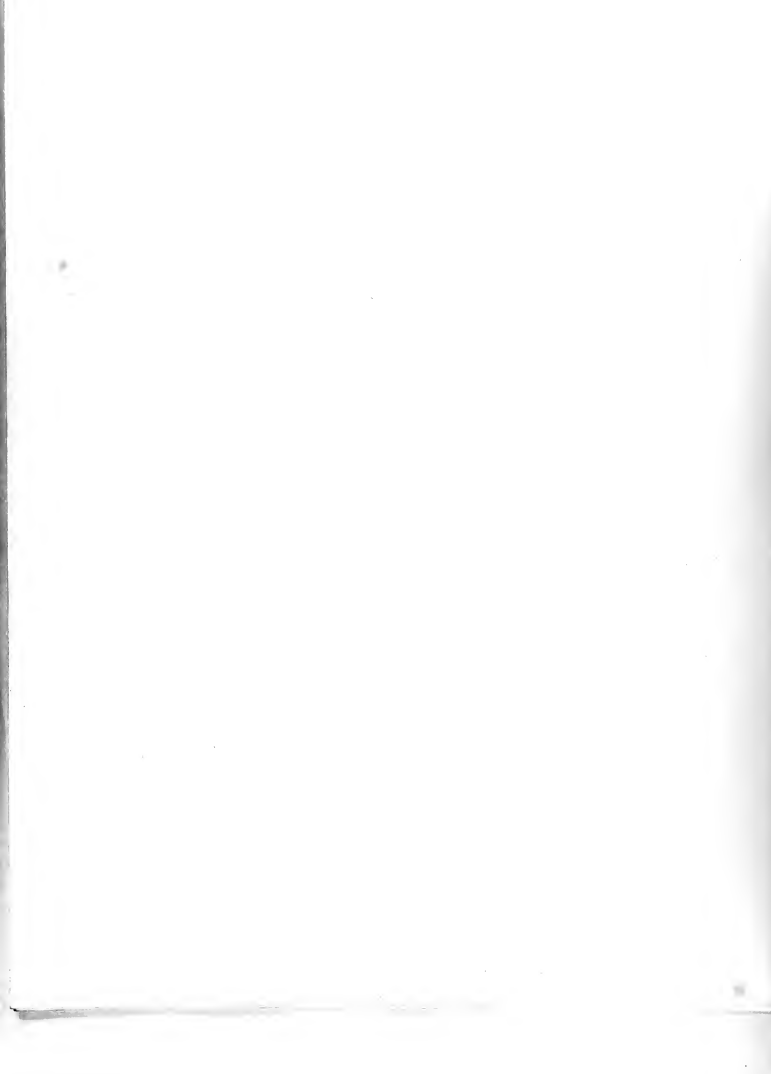
In the basic formula, (18) the no-load safety  $\tau_g$  is included as fraction of  $\Delta t_g$ , i.e. by the given  $\sigma$ , according to (23)  $\tau_g$  becomes larger or smaller, depending whether  $\Delta t_g$  becomes larger or smaller. With the help of a simple transposition, the formula (18) will take a form, in which  $\tau_g$  is independent from  $\Delta t_g$ . By inserting from (23)  $\sigma = \tau_g$  in (18) and we obtain after solution:

$$\Delta t_g = \frac{\varepsilon \theta}{\omega (1 - \beta)} + \frac{\tau_g}{(1 - \beta)} \quad (25)$$

This form of the formula will be used in many cases in the calculation of choke coils.

#### 7. The Value $\tau_g$ and the Base-load-current

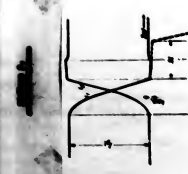
According to (25) the necessary steplength at a given  $\varepsilon, \theta$  and  $\tau_g$  is inversely proportional to  $1 - \beta$ . The value  $\beta = \frac{J_{ls} - J_{ls0}}{J_{ls}}$





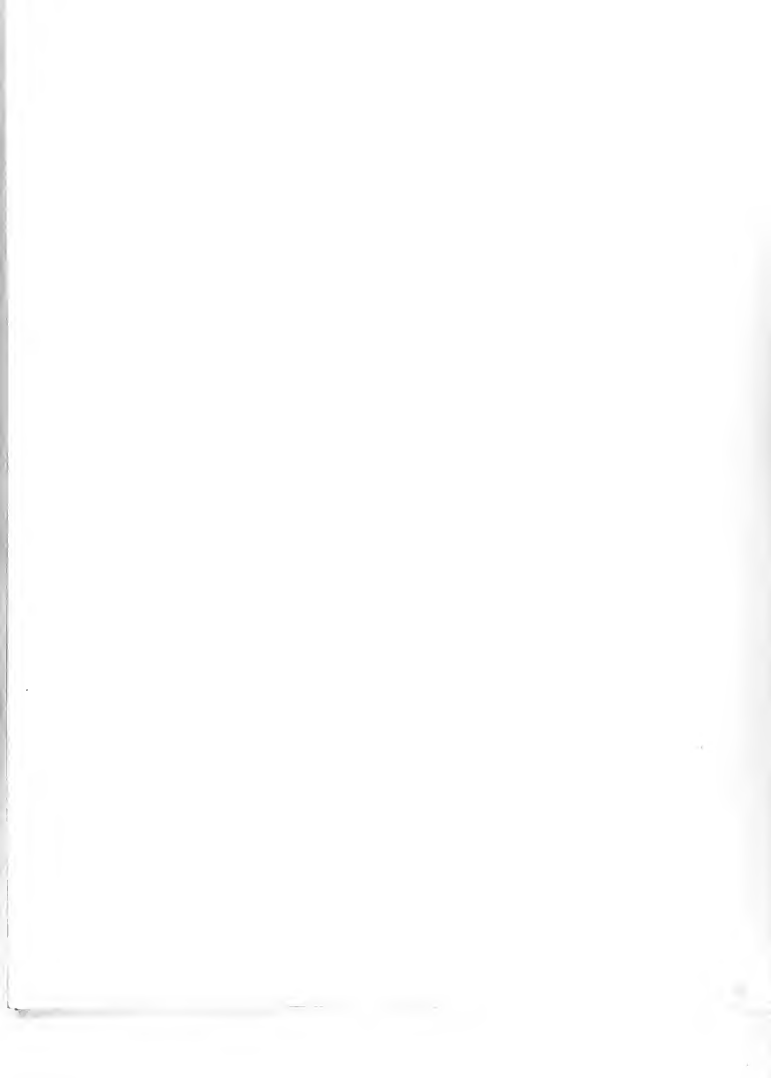
1. Lampe, 2. Lampe, 3. Lampe  
 4. Schalter (Hauptschalter)  
 5. Schalter (Zweigschalter)  
 6. Schalter (Zweigschalter)  
 7. Schalter (Zweigschalter)  
 8. Schalter (Zweigschalter)  
 9. Schalter (Zweigschalter)  
 10. Schalter (Zweigschalter)

1. Lampe, 2. Lampe, 3. Lampe  
 4. Schalter (Hauptschalter)  
 5. Schalter (Zweigschalter)  
 6. Schalter (Zweigschalter)  
 7. Schalter (Zweigschalter)  
 8. Schalter (Zweigschalter)  
 9. Schalter (Zweigschalter)  
 10. Schalter (Zweigschalter)



1. Lampe, 2. Lampe, 3. Lampe  
 4. Schalter (Hauptschalter)  
 5. Schalter (Zweigschalter)  
 6. Schalter (Zweigschalter)  
 7. Schalter (Zweigschalter)  
 8. Schalter (Zweigschalter)  
 9. Schalter (Zweigschalter)  
 10. Schalter (Zweigschalter)

1. Lampe, 2. Lampe, 3. Lampe  
 4. Schalter (Hauptschalter)  
 5. Schalter (Zweigschalter)  
 6. Schalter (Zweigschalter)  
 7. Schalter (Zweigschalter)  
 8. Schalter (Zweigschalter)  
 9. Schalter (Zweigschalter)  
 10. Schalter (Zweigschalter)



The purpose of this study is to determine the effect of the concentration of the solution on the rate of the reaction. The reaction is carried out in a closed system at a constant temperature. The rate of the reaction is measured by the change in the concentration of the reactants over time.



The graph shows that the rate of the reaction increases with the concentration of the solution. The rate of the reaction is directly proportional to the concentration of the solution.

4

218

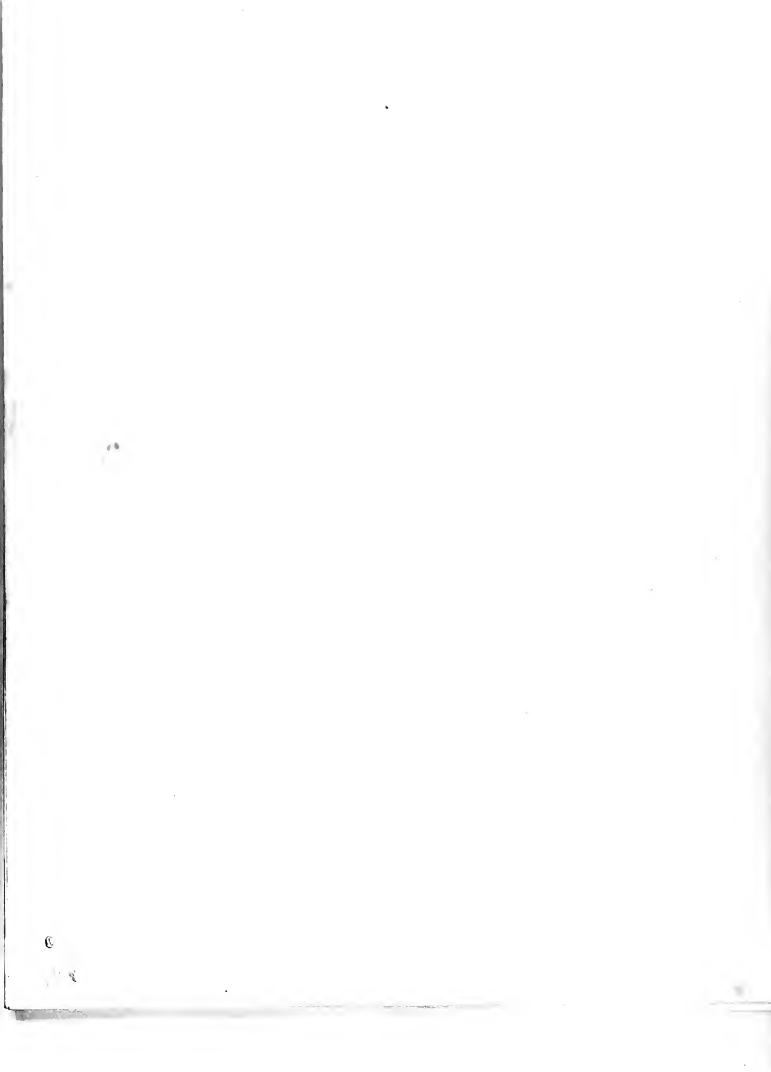
The purpose of this study is to determine the effect of the concentration of the solution on the rate of the reaction. The reaction is carried out in a closed system at a constant temperature. The rate of the reaction is measured by the change in the concentration of the reactants over time.



The graph shows that the rate of the reaction increases with the concentration of the solution. The rate of the reaction is directly proportional to the concentration of the solution.

6

212













Thesis

13133

B56

Bliss

A mechanical rectifier  
for aircraft.

Thesis

13133

B56

Bliss

A mechanical rectifier  
for aircraft.

thes856

A mechanical rectifier for aircraft.



3 2768 001 03673 4

DUDLEY KNOX LIBRARY